



PHD

**CLOSING THE GAP BETWEEN SCIENCE AND PRACTICE IN SWIMMING TESTING,
TRAINING PRESCRIPTION AND MONITORING**

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**CLOSING THE GAP BETWEEN SCIENCE AND PRACTICE IN
SWIMMING TESTING, TRAINING PRESCRIPTION AND
MONITORING**

EVA PIATRIKOVA

A thesis submitted for the degree of Doctor of Philosophy

University of Bath

Department for Health

September 2020

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Eva Piatrikova

Abstract

The regular testing and monitoring of an athletes' performance and well-being status are well-established key components of a successful training programme. However, the associated procedures are challenging to conduct in swimming practice. This is primarily due to the technological constraints of the aquatic environment, the multidisciplinary nature of swimming, and the limited time, resources, and physiological testing expertise often available to swimming coaches. The recent development of the 3-minute all-out test (3MT) and improvements in athlete heart rate variability (HRV) monitoring technology have helped to address some of these issues across a number of sports. However, their application in the sport of swimming remains to be investigated.

The first study (Chapter 3) of this thesis demonstrates that the 3MT is a valid (correlation with traditional method $r=0.95$ for CS, $r=0.79$ for D', $p\leq 0.002$), reliable (ICC=0.97, CV=0.9% for CS; ICC=0.87, CV=9.1% for D'), and feasible protocol for the assessment of the parameters describing the critical speed (CS) concept in competitive swimmers. In Chapter 4, the application of the 3MT is further extended to enable the demarcation of the remaining exercise intensity domains from CS only. In comparison to traditional step test, this method shows to represent a more valid whilst feasible approach (no statistically significant differences $p=0.93-1.00$, and nearly perfect correlations at lactate threshold $r=0.92$, and lactate turnpoint $r=0.90$, and very large correlations at maximal aerobic speed $r=0.88$; all $p<0.0001$), compared to the popular "beats below maximal heart rate" method, which produced significantly lower estimates than those established from a step test (all $p<0.03$), despite large-to-very large correlations ($r=0.63-0.89$, $p<0.03$) found between lactate threshold and lactate turnpoint (for speed and heart rate). Chapter 5 demonstrates that a seasonal training programme, individualised based on the data obtained from a regular 3MT, is associated with seasonal improvements in several important parameters of swimming performance (mean change \pm 90% confidence limits: CS: $+5.4 \pm 1.6\%$, personal best time in 1st: $-1.2 \pm 1.3\%$ and 2nd main event: $-1.6 \pm 0.9\%$, stroke rate: $+6.4 \pm 3.0\%$ and stroke index: $+4.2 \pm 3.6\%$ at CS), despite a substantial reduction ($\geq 25\%$) in the overall training volume of highly trained swimmers. Finally, Chapter 6 describes swimmers' HRV responses to a typical training season, reveals large associations between

seasonal changes in key HRV parameters and CS ($\Delta \text{Ln rMSSD}_{\text{MEAN}}$: $r=0.51$, $p=0.13$; $\Delta \text{Ln rMSSD}_{\text{CV}}$: $r=-0.68$, $p=0.03$), and demonstrates that the Banister Impulse-Response model and data collected via a novel smartphone application (HRV4Training) allow the effective monitoring and modelling of swimmers' responses to swimming training and non-training related stressors (R^2 values of 0.75-0.87).

Overall, this body of work focuses on bridging the gap between science and practice in the testing, training prescription, and monitoring of competitive swimmers and provides examples of approaches through which the existing gaps could be closed.

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Publications

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Table of contents

Abstract.....	2
Acknowledgements	4
Publications.....	5
Table of contents.....	6
List of figures	8
List of tables.....	11
Abbreviations.....	12
Chapter 1: Introduction	14
1.1 Research overview	14
1.2 Thesis overview	19
Chapter 2: Literature review	21
2.1 Swimming overview	21
2.2 The unique characteristics of swimming.....	22
2.3 Technical demands of swimming	25
2.4 Training characteristics in swimming.....	26
2.5 Exercise intensity domains.....	29
2.6 Current testing methods in swimming research and practice.....	32
2.7 Speed-duration relationship and critical speed concept.....	36
2.8 Monitoring athletes' status	50
2.9 Rationale for the current work.....	55
Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers	57
3.1 Abstract	57
3.2 Introduction	57
3.3 Methods.....	60
3.4 Results	63
3.5 Discussion.....	73
3.6 Practical applications	80
3.7 Conclusion.....	82
Chapter 4: Demarcating exercise intensity domains in swimming; Is there an alternative to incremental step test and beats below HR_{MAX} method?.....	83
4.1 Abstract	83
4.2 Introduction	83

4.3 Methods.....	87
4.4 Results	91
4.5 Discussion.....	101
4.6 Practical applications	107
4.7 Conclusion.....	110
Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts.....	111
5.1 Abstract	111
5.2 Introduction	112
5.3 Methods.....	115
5.4 Results	124
5.5 Discussion.....	133
5.6 Practical applications	145
5.7 Conclusion.....	147
Chapter 6: Monitoring heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model.....	148
6.1 Abstract	148
6.2 Introduction	149
6.3 Methods.....	151
6.4 Results	156
6.5 Discussion.....	166
6.6 Practical applications	174
6.7 Conclusion.....	175
Chapter 7: General discussion	177
7.1 Introduction	177
7.2 Addressing the research questions.....	177
7.3 The original contribution to knowledge.....	183
7.4 Practical applications and potential impact.....	184
7.5 Research impact.....	190
7.6 Future research.....	194
7.7 Conclusion.....	196
Reference list.....	198

List of figures

Figure 2.1. Distribution of the energy system contribution to the total energy demands of the freestyle competitive events. Symbols denote values corresponding to 50, 100, 200, 400, 800 and 1500 m freestyle, respectively (Rodríguez & Mader, 2010, pp. 13).	22
Figure 2.2. Responses of the oxygen uptake kinetics in the moderate, heavy, severe and extreme exercise intensity domains (Adapted from Fawcner & Armstrong, 2003).	31
Figure 2.3. Calculation of the critical speed (CS) and finite work capacity above CS (D') using (A) hyperbolic speed-time, (B) distance-time and (C) speed-inverse time ($1/T$) relationships; D , distance; T , time.	40
Figure 3.1. The group mean speed-time profile of the 3-min all-out test. * $p < 0.05$ compared to the speed in the last 30 s, † $p < 0.05$ compared to the previous 15 s speed interval, $n = 12$.	64
Figure 3.2. The derivation of the critical speed (CS) and D' estimates from the linear distance-time (A), speed- $1/\text{time}$ (B) models and a 3-min all-out test (C) in a representative subject.	65
Figure 3.3. Correlation and Bland-Altman analyses for differences in CS between the 3MT and the distance-time model (A, C) and between the 3MT and the speed- $1/\text{time}$ model (B, D). In the panels A and B, the solid line is the line of best-fit linear regression and the dashed line is the line of identity. In the panels C and D, the solid horizontal lines represent the mean difference between the CS_{3MT} and CS_{DT} and CS_{3MT} and $CS_{1/T}$, respectively, and the dashed lines represent the 95% limits of agreement; $n = 12$.	68
Figure 3.4. Correlation and Bland-Altman analyses for differences in D' between the 3MT and the distance-time model (A, C) and between the 3MT and the speed- $1/\text{time}$ model (B, D). In the panels A and B, the solid line is the line of best-fit linear regression and the dashed line is the line of identity. In the panels C and D, the solid horizontal lines represent the mean difference between the D'_{3MT} and D'_{DT} and D'_{3MT} and $D'_{1/T}$, respectively, and the dashed lines represent the 95% limits of agreement; $n = 12$.	69
Figure 3.5. The group mean stroke rate-time profile of the 3-min all-out test. * $p < 0.05$ compared to the stroke rate in the last 30 s, $n = 12$.	71
Figure 4.1. Correlation and Bland-Altman analyses for differences in lactate threshold (A,B), lactate turnpoint (C,D) and maximal aerobic speed (E,F) derived from the incremental step test and the 3-min all-out test. In the panels A, C and E, the solid line is the line of best-fit linear regression, the dashed line is the line	

of identity. In the panels B, D and F, the solid lines represent the mean difference between $LT_{IST} - LT_{3MT}$, $LTP_{IST} - LTP_{3MT}$, $S_{MAX-IST} - S_{MAX-3MT}$, respectively, the dashed lines represent the 95% LOA; n=13.	95
Figure 4.2. Actual versus predicted speed at (A, B) lactate threshold, (C, D) critical speed, (E, F) lactate turnpoint, using the beats below HR_{MAX} method. The solid line is the line of best-fit linear regression and the dashed line is the line of identity; n=13.	98
Figure 5.1. Average total volume and intensity distribution during a 15-week intervention period. The error bars represent standard deviations.....	125
Figure 5.2. Mean speed-time profiles for the 3-min all-out tests for baseline and tests 1-3.....	128
Figure 5.3. Changes in critical speed (A), D' (B), $speed_{150s}$ (C) and $speed_{180s}$ (D) from baseline to tests 1-3. Data are presented as means \pm 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects.	129
Figure 5.4. Changes in peak speed (A) and predicted 200 m time (B) from baseline to tests 1-3, and in PBs for 1 st (C) and 2 nd main event (D). Data are presented as means \pm 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects.	130
Figure 5.5. Changes in stroke length (A), stroke index (B), stroke rate (C) and stroke count (D) adopted at critical speed from baseline to tests 1-3. Data are presented as means \pm 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects.	132
Figure 6.1. Weekly mean heart rate variability responses and mean sum of the sRPE for the 15-week period. Grey shaded area represents the smallest worthwhile change. S, M and L refer to small, moderate and large effect sizes, respectively. The effect size values reported below and above the “line of mean responses”, represent consecutive week-to-week changes and changes from baseline (week 1) values, respectively. Error bars represent 95% confidence limits for $Ln\ rMSSD_{MEAN}$ and $Ln\ rMSSD_{CV}$ and standard deviations for sRPE. Stress/illness refers to a week when majority of swimmers (i.e., n=6) experienced non-training related stress and/or illness.	158
Figure 6.2. Relationships between seasonal changes (Δ) in critical speed and heart rate variability measures of $Ln\ rMSSD_{MEAN}$ (A) and $\Delta\ Ln\ rMSSD_{CV}$ (B) (n=10).....	159
Figure 6.3. Modelling HRV responses using sRPE alone and in combination with the best subjective wellness score in the swimmers 1-4.	162

Figure 6.4. Modelling HRV responses using sRPE alone and in combination with the best subjective wellness score in the swimmers 5-8.	163
Figure 6.5. Modelling HRV responses using sRPE alone and in combination with the best subjective wellness score in the swimmers 9-10.....	164

List of tables

Table 2.1. Description and training intensity measurement utilised by swimming coaches, national training centres and delivered as a part of the swimming coaching curriculum in United Kingdom (Peyrebrune, 2005).....	35
Table 3.1. Comparison of the critical speed and D' derived from the 3-min all-out test and conventional models.....	66
Table 3.2. Comparison of the actual versus predicted time trial times.....	67
Table 3.3. Test-retest reliability of the 3-min all-out swimming tests.....	72
Table 4.1. Training intensity measurement utilised by swimming coaches, national training centres and delivered as a part of the swimming coaching curriculums.....	85
Table 4.2. Comparisons of the speed measures derived from the incremental step test and 3-min all-out test.....	92
Table 4.3. Comparisons of the speeds at lactate threshold, lactate turnpoint and maximum aerobic speed derived from 3-min all-out test and the incremental step test.....	94
Table 4.4. Comparisons of the speed at lactate threshold, lactate turnpoint and critical speed derived from the incremental step test and 3-min all-out test to the beats below HR _{MAX} method.	97
Table 4.5. Comparisons of the heart rate at lactate threshold and lactate turnpoint derived from the incremental step test and the beats below HR _{MAX} method.	100
Table 5.1. General and performance characteristics of the recruited competitive swimmers.	116
Table 6.1. General and performance characteristics of the swimmers.	152
Table 6.2. Estimates of model parameters using the Banister model.	161
Table 6.3. Comparison of the model fit (R^2) when sRPE in combination with subjective wellness scores is used to model HRV responses.	165
Table 7.1. An initial conceptual framework of training intensity zones applying the critical speed concept in swimming.....	186

Abbreviations

Δ -change

[La⁻]/BLa- blood lactate concentration

1/T- speed-1/time model

3MT- 3-min all-out test

ANS- autonomic nervous system

BBM-beats below maximal heart rate

bpm- beats per minute

CI-confidence intervals

CL-confidence limits

CM- conventional methods

CP-critical power

CS-critical speed

CSR- critical stroke rate

CV- coefficient of variation

D-T model- distance-time model

D'/W'- finite capacity to exercise above critical speed/power

D₁₅₀- distance at 150 seconds

D₁₈₀-distance at 180 seconds

ES-effect size

GET-gas exchange threshold

HF-high frequency

HIIT- high intensity interval training

HR-heart rate

HR_{MAX}- maximal heart rate

HRV- heart rate variability

I-R model- Impulse-Response model

IAT- individual anaerobic threshold

ICC- intra-class correlation coefficient

IST-incremental step test

LIT- low intensity training

Ln- natural logarithm

LOA-limits of agreement

LT-lactate threshold
 LTP-lactate turnpoint
 MBI-magnitude based inferences
 MLSS- maximal lactate steady state
 OBLA- onset of blood lactate accumulation
 PB- personal best time
 r- Pearson's correlation
 R²-coefficient of determination
 RCP- respiratory compensation point
 rMSSD- Root Mean Square of the Successive Differences
 SD- standard deviation
 SE-standard error
 SEE- standard error of the estimate
 SI-stroke index
 SL-stroke length
 S_{MAX}- maximal aerobic speed
 Speed_{150s}-speed at 150 seconds
 Speed_{180s}-speed at 180 seconds
 Speed_{4MMOL}- speed at blood lactate concentration of 4 mmol
 SR- stroke rate
 sRPE- session rating of perceived exertion
 SWC- smallest worthwhile change
 T@ $\dot{V}O_{2MAX}$ - time spent above 90% of $\dot{V}O_{2MAX}$
 TE-typical error
 TT-time trials
 TTE- time to exhaustion
 $\dot{V}O_2$ - oxygen uptake
 $\dot{V}O_{2max}$ - maximal oxygen uptake
 $v\dot{V}O_{2max}$ - minimum velocity that will elicit $\dot{V}O_{2max}$
 WR-world record

Chapter 1: Introduction

1.1 Research overview

Swimming is a water sport that was part of the first modern Olympic Games in 1896. Since then, spectators have witnessed countless races in which just hundredths of a second have determined the outcome of the race and medal positions. As a result of this, swimmers are known to commit long hours to training to perfect their craft and achieve the smallest time improvements, in the hope of increasing their chances of qualifying for finals and competing for prestigious medal positions (Nugent, Comyns and Warrington, 2017). For example, in the 100 m freestyle at the Rio 2016 Olympics, just 0.27 s and 0.29 s separated both men's and women's Olympic champions from bronze medallists, and only 0.56 s and 0.37 s separated the latter from the 8th ranked swimmer, respectively. Swimming is also one of the few sports in which athletes have the opportunity to race in numerous events. Specifically, swimmers have the opportunity to race in four different strokes (butterfly, backstroke, breaststroke, and freestyle), or of their combination in the individual medley, over distances ranging from 50 m to 1500 m. This subsequently makes swimming one of the largest Olympic sports, with 27 official swimming events approved by the Fédération Internationale de Natation (FINA).

Considering the multidisciplinary challenges of swimming and the multifaceted nature of performance itself, over the years swimming coaches and scientists from various disciplines have worked hard behind the scenes to develop training programmes that allow swimmers to maximise their potential when it matters the most (Smith, Norris and Hogg, 2002). Naturally, this has resulted in more scientific information, progressive and substantial improvements in training approaches and swimming performance itself. However, as recently highlighted, the translation of the ever-increasing scientific findings to the applied world has been an 'Achilles heel' for many sports, including swimming, which currently faces several obstacles standing in the way of 'closing the gap' between these two worlds (Buchheit, 2017).

Firstly, there is a dearth of methods allowing swimming coaches to conduct physiological testing that provides a valid picture of athlete's physiological capabilities and changes on a regular basis (e.g., at the end of each training cycle),

Chapter 1: Introduction

especially for those with limited resources. Indeed, the traditional incremental step tests (IST) or square wave testing approaches are demanding to conduct for the majority of swimming coaches, who often coach large groups of swimmers and have a limited amount of time, resources, and physiological testing expertise available to them (Roos et al., 2013). As a result, coaches often choose more feasible methods (e.g., time trials, personal best times, percentage of maximal heart rate) that may provide a limited picture of a swimmer's physiological profile and development. Therefore, there is clearly a need for methods that provide coaches with valid and reliable physiological information across all swimming strokes and its components, but that also have the capacity to be applied on a regular basis in environments where the limited amount of resources, time and testing expertise need to be considered on a daily basis (i.e., the vast majority of swimming clubs).

Additionally, examining changes in the parameters of the aerobic system have traditionally received more attention from scientists and coaches, despite the fact that the contribution of the anaerobic system in swimming events is substantial (Rodríguez and Mader, 2010). In the research literature, the anaerobic capacities of swimmers have mostly been assessed by measuring peak blood lactate concentrations or maximal accumulated oxygen deficit (Smith, Norris and Hogg, 2002). However, these procedures require expensive equipment and a high level of physiological expertise. Consequently, coaches often use shorter efforts (e.g., 10-50 m sprints) as a normative way to track changes in anaerobic capacities of the swimmers. This further highlights the need for a practical test that could enable coaches to monitor the impact of training on changes in *both* aerobic and anaerobic components.

The critical speed (CS) concept represents a compromise between validity and practicality, and could therefore overcome some of the aforementioned challenges (Pettitt, 2016; Vanhatalo, Jones and Burnley, 2011). The CS concept identifies CS as the boundary (i.e., “threshold”) between heavy (sustainable) and severe (non-sustainable) exercise intensity domains (Jones et al., 2019; Jones et al., 2010). The CS is thus the highest speed one can sustain without increasing unsustainable metabolic perturbations, and provides information on the athlete's aerobic capacity (Jones et al., 2019; Jones et al., 2010). The CS concept also identifies the D prime (D') parameter, which represents an athlete's finite capacity and tolerance to perform high intensity

Chapter 1: Introduction

exercise above their CS, and so is believed to mainly capture the contribution of the anaerobic system (Jones et al., 2010). Despite the ability of the concept to provide key physiological information, it has not been extensively applied in swimming practice despite being introduced in the 1960's (Monod and Scherrer, 1965). This is perhaps due to the cumbersome nature of the traditional assessment procedures, which requires the completion of multiple time trials interspersed across several days. This has precluded the uptake of this concept by the wider swimming coaching community (Jones et al., 2010; Dekerle, 2006). Therefore, a protocol that can provide this information, across multiple strokes, in a single visit and on a regular basis is needed to allow coaches to benefit from the large practical applications the CS concept could offer to the community of swimming practitioners (Pettitt, 2016; Jones et al., 2010).

In sports completed on land, but especially for cycling and running, a promising alternative protocol to determine CS (critical power (CP)-for cycling) and D' (W' for cycling) estimates in a single session, known as the "3-min all-out test" (3MT), has been developed and validated by Vanhatalo, Doust and Burnley in 2007. The 3MT protocol has emerged from the theory underpinning CS/CP concept and speed(power)-duration relationship (Jones et al., 2010). Specifically, by asking an athlete to exercise "all-out" from the beginning, the authors demonstrated that the power will naturally drop, representing depletion of W', and will reach a plateau in the last 30 s of the test, representing the highest power one can physiologically maintain following W' depletion i.e., CP (Burnley, Doust and Vanhatalo, 2006; Vanhatalo, Doust and Burnley, 2007). Since the first validation of the 3MT in cycling, the protocol has been tested and applied in multiple sports such as running (Broxterman et al., 2013), rowing (Cheng et al., 2012) and shuttle running (Saari et al., 2019). Despite the promising findings of Tsai and Thomas (2017) in recreational swimmers, the validity and reliability of the 3MT in competitive swimmers remains to be investigated.

Since the first validation of the 3MT, multiple studies have also explored the application of the CS concept for training prescription (Clark et al., 2013; Courtright et al., 2016; Vanhatalo, Doust, Burnley, 2008a). For example, Francis et al. (2010) demonstrated that CP from 3MT could be used by cycling coaches, who do not have access to IST, to estimate thresholds demarcating the remaining exercise intensity domains. Given that establishing training zones for individual swimmers on a regular

Chapter 1: Introduction

basis is often challenging for swimming coaches, it would be useful to examine if the approach utilised by Francis et al. (2010) could be replicated with the same success in swimming, and whether it would be more accurate for demarcating intensities compared to one of the most commonly-used approaches in swimming practice; the ‘beats below HR_{MAX} ’ method (BBM), which has not been validated to date, despite its widespread use.

Furthermore, utilising the data from 3MT for the prescription of individualised high-intensity interval training (HIIT) has recently gained traction in research (Pettitt, 2016). Whilst the minimum velocity eliciting maximum oxygen uptake ($v\dot{V}O_{2MAX}$) has been used for research purposes (Buchheit and Laursen, 2013), in swimming practice, HIIT is typically prescribed based on more affordable methods (e.g., BBM, anaerobic threshold, race-pace velocities, personal best times, holding best average), which do not take into account the between-athlete differences in anaerobic and/or aerobic capacities. The 3MT may therefore provide a solution to this problem. To date, only short-term training studies (4 weeks) have explored this individualised HIIT approach (Courtright et al., 2016; Clark et al., 2013, Vanhatalo, Doust and Burnley, 2008a), and so longitudinal studies that monitor changes in several parameters (e.g., physiological, technical, performance) are required to explore the efficacy and practicality of this approach in swimming.

From a different perspective, accumulating evidence suggests that a shift towards lower volume, higher-intensity training may be as effective (or more effective) strategy compared to traditional swimming training, which often encompasses high-volumes at low intensity (Nugent et al., 2017). Therefore, it would be useful to examine whether individualising HIIT training based on the CS concept and 3MT would result in beneficial improvements in swimming parameters, despite substantial reductions in training volume of competitive swimmers. This work would therefore contribute to the ongoing ‘Quality versus Quantity’ debate in the swimming community (Nugent, Comyns and Warrington, 2017), but more importantly, could provide evidence that high volumes of training are not *necessary* for success in swimming. This could have substantial implications for swimmers’ health (e.g., shoulder injury prevention) and well-being (burnout prevention), alongside benefits

Chapter 1: Introduction

for coaches who often have limited pool time but still seek to optimise training prescription.

Indeed, building on processes of effective and efficient training prescription, heart rate variability (HRV) has become a promising monitoring tool utilised by an increasing number of sport science teams to take the principle of training individualisation a step further (Plews et al., 2013a). Specifically, measuring the activity of the parasympathetic system via HRV offers practitioners an insight into the global responses of athletes to training and non-training related stressors. Multiple studies have shown that HRV is related to performance (Chalencon et al., 2012; 2015), training load (Flatt, Hornikel and Esco, 2017), health (Hellard et al., 2011) and psychological status of an athlete (Flatt, Esco and Nakamura, 2018; Flatt, Hornikel and Esco, 2017), making HRV an increasingly popular measure. One of the recent promising applications of HRV monitoring is its ability to track changes in performance without the need to actually measure the performance itself. This approach was explored by Chalencon et al. (2012), who utilised the Banister Impulse-Response (I-R) model to monitor and model both performance and HRV responses to training load in competitive swimmers. Chalencon et al.'s (2012) data indicated that HRV can be used to track changes in swimming performance. However, whilst this approach reduces the need for coaches to conduct the frequent performance tests typically required for I-R modelling, the methods used by Chalencon et al. (2012) were still not feasible for many sport practitioners. Specifically, the need for HR straps, measuring HRV during sleep, and calculating training load based on seven different exercise intensities, could present challenges to the compliancy of athletes and coaches to benefit from this approach on a long-term basis. Fortunately, technological advances in recent years have enabled valid HRV measurements to be collected in 1 minute using just a smartphone (Plews et al., 2017). It would therefore be useful to explore whether the findings of Chalencon et al. (2012) could be replicated when more user-friendly approaches are used to monitor and model HRV responses to training as well as non-training related stressors. These data would also allow us to describe the typical responses of swimmers to various phases of the season (e.g., overload, recovery, overseas camp, taper, and competitions), which is currently limited in the research literature (Flatt, Hornikel and Esco, 2017).

Chapter 1: Introduction

Accordingly, the following research questions will be addressed in this thesis, with the overarching aim being to contribute to ‘closing the gap’ between science and practice in testing, training prescription and monitoring in competitive swimming:

1. Does the 3-min all-out test have acceptable validity and reliability in highly-trained swimmers?
2. Can the 3-min all-out test be used to accurately estimate exercise intensity domains in highly-trained swimmers?
3. How accurate is the ‘beats below HR_{MAX} ’ method in determining exercise intensity domains of highly-trained swimmers?
4. Can the 3-min all-out test data be used to individualise highly-trained swimmers’ programmes, and produce beneficial improvements in performance, despite substantial reductions in training volume?
5. What are the typical seasonal HRV responses of highly-trained swimmers?
6. Is there a relationship between seasonal changes in key HRV parameters and CS?
7. Can session Rating of Perceived Exertion (sRPE) be used to model HRV responses of swimmers utilising the I-R model?
8. Does the accuracy of model fit improve when subjective wellness measures are added to the I-R model?

1.2 Thesis overview

These research questions will be addressed in the six chapters outlined below:

- Chapter 2 provides a review of the literature related to the aforementioned research questions. Briefly, this includes a review of the literature discussing the demands and determinants of swimming performance, an overview of the testing and monitoring procedures currently used in swimming, and an overview of the CS concept and HRV and their application in various sports, including swimming.
- Chapter 3 examines the validity and reliability of the 3MT in comparison to the time trial protocol traditionally utilised to calculate CS and D' .
- Chapter 4 explores the utility of 3MT to estimate the remaining exercise intensity domains, and also investigates the validity of the ‘20-30’ and ‘40-

Chapter 1: Introduction

50' beats below HR_{MAX} method currently utilised by swimming coaches to establish training zones for swimmers.

- Chapter 5 explores the utility and effectiveness of the 3MT for regular assessment and prescription of individualised HIIT training programmes in highly-trained swimmers (with a $\geq 25\%$ reduction in training volume) throughout a short-course season.
- Chapter 6 describes typical HRV responses of swimmers to a seasonal training programme (including periods of overload, recovery, and taper) and explores their associations with changes in critical speed. This chapter also explores whether the I-R model, and the data obtained from a novel monitoring smartphone application that collects HRV, training load and subjective wellness data, can be used to model and monitor HRV responses to training and non-training related stressors.
- Chapter 7 provides a general discussion of this thesis's findings and outlines their originality within the current state of knowledge. The practical applications and impact (both realised and potential) of this work is presented. Finally, suggestions for future research studies are offered.

Chapter 2: Literature review

2.1 Swimming overview

The main goal in competitive swimming is to cover the specified race distance, which in swimming ranges from 50 m to 1500 m, in the fastest time. Swimmers have opportunity to race these in four different strokes, or of their combination in the individual medley, whereby swimmers complete one quarter of the distance in each stroke in the following set order: butterfly, backstroke, breaststroke and freestyle. Based on decreasing order of record speeds, freestyle, also known as front crawl, is the fastest stroke followed by butterfly, backstroke and breaststroke. Swimming events are typically swam in short-course (25 m) and long-course ‘Olympic’ (50 m) swimming pools as the season progresses from autumn-winter to spring-summer, respectively. The swimming events are classified into sprint (50 m, 100 m), middle (200 m, 400 m), and long distances (800 m, 1500 m) (Pyne and Sharp, 2014). In elite competitive swimming, these events typically last from ~22 s (50 m) up to ~14-16 min (1500 m). Considering the relationship between exercise duration and energy pathways, this has implications for the energy systems utilised in swimming (Rodríguez and Mader, 2010). Whilst sprint distance swimmers rely predominantly on the high-energy phosphate system (ATP, [PCr]) and anaerobic glycolysis, with increasing distance and duration the contribution from oxidative phosphorylation increases (see **Figure 2.1**) (Rodríguez and Mader, 2010). Indeed, the contribution to total energy expenditure from the aerobic system of ~25-30% in 50 m; ~40-55% in 100 m, ~70% in 200 m and ~80%< for events of 400 m and beyond, are typically reported in the literature examining the relative contribution of energy systems, with the remaining energy being generated through the combined contribution of anaerobic systems (i.e., anaerobic lactic and alactic) (Mitchell, 2019; Zamparo, Capelli and Pendergast, 2011). This emphasises the importance of understanding the determining energy systems in a given event for training prescription. It is, however, also important to emphasise that although training programmes and research studies have traditionally focused upon developing and examining the aerobic system, the anaerobic systems should not be neglected given that in the majority of swimming events (i.e., 50 m – 200 m) this system contributes in the range of ~25-75% of total energy production (Mitchell, 2019; Zamparo, Capelli and Pendergast, 2011).

Chapter 2: Literature review

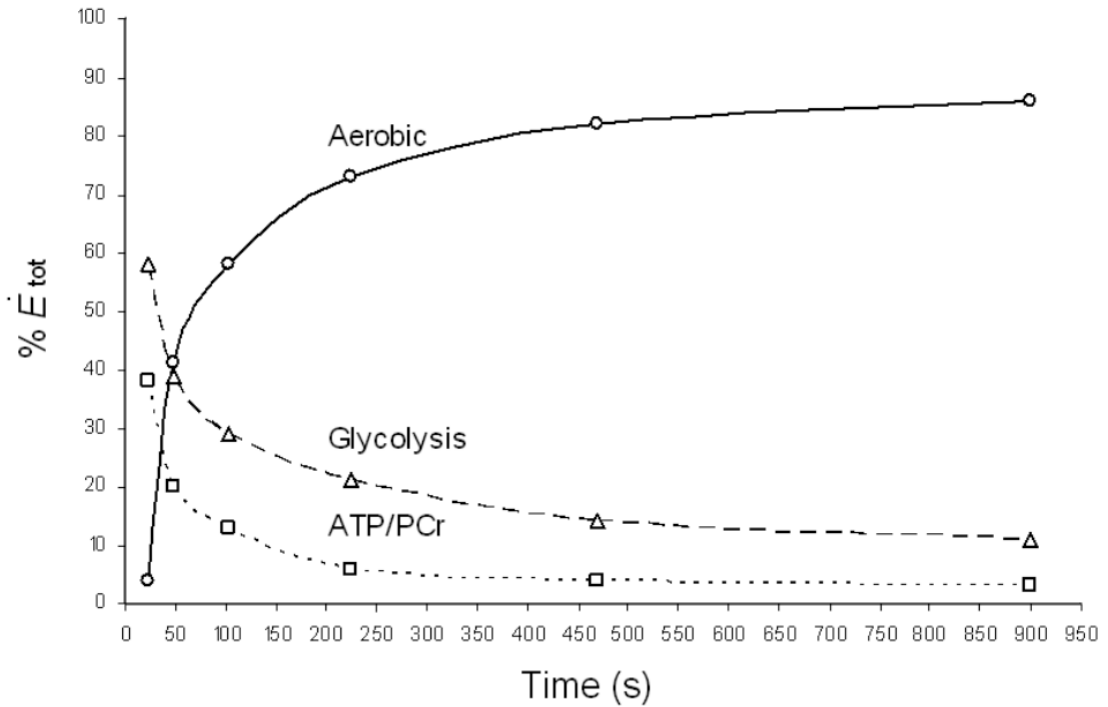


Figure 2.1. Distribution of the energy system contribution to the total energy demands of the freestyle competitive events. Symbols denote values corresponding to 50, 100, 200, 400, 800 and 1500 m freestyle, respectively (Rodríguez & Mader, 2010, pp. 13).

2.2 The unique characteristics of swimming

As mentioned above, the main goal of competitive swimmers is to swim the given event in the shortest time possible. To achieve this, swimmers strive to develop and maintain the highest speed for the duration of the race, which is a product and interplay of multiple factors (i.e., physiological, technical, tactical, and psychological) (Smith, Norris and Hogg, 2002). Although this goal is similar to other sports, the aquatic environment of swimming imposes unique challenges and stressors on the body, compared to those observed in sports completed on land (Sousa et al., 2015a;b; Aspenes and Karlsen, 2012), and the practitioners should be aware of these in order to work effectively.

Firstly, during swimming, a swimmer's breathing is restricted and it is also synchronised with the head action and arm movements associated with the specific stroke technique. In all strokes except for backstroke, the inspiration phase is time-restricted, and the expiration phase is performed under the water against resistance. This, together with hydrostatic pressure on the body, places greater demand on the

Chapter 2: Literature review

respiratory system in swimming compared to land-based sports (Lazovic-Popovic et al., 2016; Aspenes and Karlsen, 2012). Previous research studies reported changes in respiratory muscle function as well as enhanced pulmonary structure and function (e.g., larger lung capacities) in swimmers when compared to other performance-matched athletes engaging in land-based sports (Rosser-Stanford et al., 2019; Lazovic-Popovic et al., 2016; Aspenes and Karlsen, 2012; Clanton et al., 1987). Lazovic-Popovic et al. (2016) attributed these changes to genetic predisposition and/or the swimming training that includes a specific way of breathing, the body position and surrounding medium. Indeed, these factors have been shown to impact upon multiple physiological determinants of sports performance. Whilst Sousa et al. (2015a;b) reported slower oxygen uptake on-kinetics and off-kinetics in swimming compared to running, cycling and rowing, Sousa et al. (2018) observed ~ 8 and $\sim 15\%$ lower $\dot{V}O_{2MAX}$ values in swimmers compared to rowers and runners, respectively. Additionally, Graef and Martins Krueel (2006) reported ~ 10 - 20 beats per minute lower heart rate (HR) peak values (Holmér, 1992), when swimming was compared to running. The previous research attributed this to lower muscle perfusion, altered hemodynamics, reduced gravity and/or the impaired ability to produce maximal muscle contractions due to the impact of the water environment, being an unstable medium (Sousa et al., 2015a;b, Libicz et al., 2005; Koga et al., 1999).

Secondly, the energy cost of human movement differs significantly between land and water (di Prampero, 1986). di Prampero (1986) compared the energy cost (i.e., the amount of energy required to travel a meter) of several forms of human locomotion of comparable exercise duration on land and in water. The findings indicated that energy expenditure was highest during swimming ($20 \text{ J.Kg}^{-1}.\text{m}^{-1}$ for 1500 m freestyle at 1.67 m.s^{-1}), being 4.7 and 8.7 times greater than 5 km running and 10 km cycling, respectively. Indeed, the density of water is ~ 800 times greater than that of air, which has significant implications on the mechanical efficiency and energy cost of swimming, which increases exponentially with speed (Capelli et al., 1998, Figueiredo et al., 2011; Barbosa et al., 2008). This emphasises the importance of developing technical skills, which might be of a greater importance for swimming as opposed to other endurance sports completed on land (Barbosa et al., 2008).

Chapter 2: Literature review

In swimming, the propulsion is generated by the synchronous and asynchronous action of both arms and legs, whilst the torso stabilises the movement and supports body rotation. Although swimming is a whole-body exercise, it predominantly relies on upper body muscle mass (80-90% contribution), with contribution to propulsion from the legs varying greatly between strokes (Bartolomeu et al., 2018; Ribeiro et al., 2015; Toussaint and Beek, 1992; Maglisho, 2003). Indeed, one of the unique features of swimming when compared to other sports is that swimmers compete in the races that not only differ in distance, but technique as well. Whilst breaststroke and butterfly are symmetrical strokes, backstroke and front-crawl are asymmetrical, which has further implications on the energy cost of swimming (Capelli et al., 1998; Barbosa et al., 2006). Capelli et al. (1998) used indirect calorimetry to investigate the energy cost of front-crawl, backstroke, breaststroke and butterfly in twenty elite swimmers at sub-maximal and maximal speeds. When the energy cost was compared across all four strokes at swimming speeds of $1 \text{ m}\cdot\text{s}^{-1}$ and $1.5 \text{ m}\cdot\text{s}^{-1}$, the authors demonstrated that breaststroke ($1.24 \text{ kJ}\cdot\text{m}^{-1}$ and $1.87 \text{ kJ}\cdot\text{m}^{-1}$) was the least economical stroke followed by butterfly ($0.84 \text{ kJ}\cdot\text{m}^{-1}$ and $1.55 \text{ kJ}\cdot\text{m}^{-1}$), backstroke ($0.84 \text{ kJ}\cdot\text{m}^{-1}$ and $1.47 \text{ kJ}\cdot\text{m}^{-1}$) and front-crawl ($0.7 \text{ kJ}\cdot\text{m}^{-1}$ and $1.23 \text{ kJ}\cdot\text{m}^{-1}$). In addition to this, Capelli et al. (1998) found that the energy cost increased exponentially with increases in speed in front-crawl, backstroke and butterfly, but increased linearly in breaststroke. The exponential relationship between speed and energy cost has been attributed to the hydrodynamic drag swimmers encounter as well as changes in stroke efficiency as the speed increases (Dekerle et al., 2006; Dekerle et al., 2005b; Pelarigo et al., 2016; Barden and Kell, 2009).

Although swimming economy varies between swimming strokes, the main difference in swimming economy between elite and sub-elite swimmers has been attributed to body anthropometrics, morphology, the speed of swimming but especially to swimmers' technical ability (Pyne and Sharp, 2014; Chatard et al., 1990; Arellano et al., 1994; Jesus et al., 2011; Toussaint and Truijens, 2005). As early as the 1980s, the pioneering studies of Holmér (1979) and di Prampero (1986) investigated the difference in energy cost between elite and sub-elite swimmers swimming at the same submaximal speed and same stroke, and found that elite swimmers are characterised by a value of the energy cost that is ~20-40% lower when compared to sub-elite swimmers. Specifically, the fastest swimmers are those that can generate and sustain

Chapter 2: Literature review

the greatest propulsive forces, i.e., speed to overcome the resistance forces of drag in an efficient and effective manner for the duration of the race. This is, however, not only a product of exceptional physiology, but exceptional technique too (Pyne and Sharp, 2014). Indeed, once swimmers reach an elite level, working on the swimmers' technical ability to transfer muscular force to applied swimming force arguably represents a greater window of opportunity for performance improvements as the physiological capacity could be closer to maximal at this point of a career (Arellano, 1999; Barbosa et al., 2008).

2.3 Technical demands of swimming

Many coaches and sports science practitioners compare a swimmer's body to a chain, where each link of the chain represents each segment of the swimmer's body, to emphasise the role of the musculoskeletal system and its coordinated effort to maintain the body position that maximises efficiency of the body moving through the water (McLeod, 2010; Smith, Norris and Hogg, 2002). One of the factors swimmers have to overcome by mastering technical proficiency is maximising propulsive forces whilst minimising the resistive forces of a water medium (Barbosa et al., 2008). The main technical components of swimming that are typically monitored in order to assess this swimmer's ability are stroke rate (SR) and stroke length (SL), the combination of which dictates swimming speed. Swimmers typically increase swimming speed by a combination of increasing SR and/or SL. Whilst SR represents a number of stroke cycles a swimmer takes per minute ($\text{cycles}\cdot\text{min}^{-1}$), SL represents the distance a swimmer covers in one stroke cycle ($\text{m}\cdot\text{cycle}^{-1}$). When applying this to a physics equation for the power calculation (i.e., $\text{Power} = \text{Speed} \times \text{Force}$), SR could represent the speed i.e., how quickly arms turn, whilst force is dictated by SL i.e., the propulsive force applied on to the water. Although, both of these speed components are fundamental to develop as swimmers progress with their training, SL has been emphasised by research studies examining the technical determinants of swimming performance as the most critical factor in achieving superior performance of elite swimmers (Arellano et al., 1994; Jesus et al., 2011; Smith, Norris and Hogg, 2002). Compared to sub-elite swimmers, elite swimmers are characterised by longer SL as well as higher stroke efficiency index (SI), which describes the ability of swimmers to swim at a given speed with the fewest number of strokes (Arellano et al., 1994; Costill et al., 1985; Jesus et al., 2011). To improve the technical parameters of swimming, a

Chapter 2: Literature review

long-term goal of swimmers is to increase SL whilst minimising any decline in SR, but in the short-term (e.g., within a race), swimmers should focus on increasing SR whilst maintaining SL (Smith, Norris and Hogg, 2002). To do so, swimmers and coaches often utilise SR or stroke count (SC), which represents the number of strokes taken by a swimmer per swimming pool length. Specifically, in training, swimmers use SC or SR with the aim of decreasing the number of strokes they spontaneously take per length or minute at a given speed, whilst maintaining this speed. This is subsequently manifested in swimmers' adopting and maintaining a greater SL. Indeed, this 'double task constraint' approach has been proposed as an effective strategy to employ in order to elicit and stabilise new technical changes in a swimming stroke (Alberty et al., 2008; Alberty et al., 2011; Seifert et al., 2007). In order to develop the aforementioned components of technical efficiency, swimmers often work on the kinematic elements of their stroke. These include entry/catching phase (e.g., hand positioning), pulling through/propulsive phase (e.g., elbow angle, sculling, arm displacement i.e. index of coordination), recovery phase (arm displacement), body rotation and leg kicking. These concepts are beyond the scope of this thesis, however further detailed information can be found in the review of McCabe (2008).

2.4 Training characteristics in swimming

Despite the relatively short duration (< 5 min) of the majority (>80%) swimming competitive events, high volumes of training have been reported in competitive swimmers (Nugent et al., 2017; Chatard and Steward, 2011; Faude et al., 2008). Competitive swimmers typically complete 9-14 swimming sessions alongside 2-3 strength and conditioning sessions a week, accumulating a volume of ~40-70 km.week⁻¹, which can equate to ~16-25 swimming hours.week⁻¹ (Nugent, Comyns and Warrington, 2017; Chatard and Steward, 2011). Although the training volume can vary based on swimmers' specialisation in stroke, distances and time in the season, it is generally assumed amongst swimming coaches that improvements in swimming performance are directly related to the volume of training performed, and that high training volumes are required to optimise physiological and technical abilities of a swimmer (Costill et al. 1991; Nugent, Comyns and Warrington, 2017; Greyson et al., 2010). Multiple research studies conducted over the last ~20 years have questioned this volume-based philosophy and have proposed alternatives with lower volumes but higher intensity training, which has resulted in the 'Quantity versus Quality' debate

Chapter 2: Literature review

(Nugent et al., 2017; Nugent, Comyns and Warrington, 2017). A growing body of research suggests that a high-volume of low-intensity training provides limited performance advantage over higher-intensity, lower volume training strategies (Kilen et al., 2014; Faude et al., 2008; Nugent et al., 2017). Additionally, excessive focus on high-volume training has been linked to increased risk of overuse injuries (Sein et al., 2010; Tovin, 2006), overtraining (Meeusen et al., 2013), early specialisation, burnout or dropout from the sport (Lloyd et al., 2015).

Costill et al. (1991) was amongst the first studies to investigate the influence of training volume on adaptation to swimming training in twenty-four collegiate swimmers. Although training volume was increased from 5 km.d⁻¹ to 9.4 km.d⁻¹ over 6 weeks in the intervention group, whilst a control group maintained their normal training (i.e., ~ 5 km.d⁻¹), the results of this study showed that larger training volumes did not significantly increase aerobic nor anaerobic capacities above those attained by the control group, and maximal sprint performance was significantly reduced in the group completing larger training volume. A similar study conducted by Ryan et al. (1990) investigated the effects of increasing volume on anaerobic threshold speed over a period of five months in fourteen elite swimmers. The results from this study indicated that increases in volume above 49 km.week⁻¹ had no effect on the speed at anaerobic threshold. To investigate this area further, Mujika et al. (1995) divided eighteen national and international swimmers in a group that performed better (improved their personal best [PB]) and worse (no improvement in PB) in the previous season and retrospectively compared these groups with regards to their training content. The authors reported that training volume, ranging from 749 km to 1475 km for a season did not significantly correlate with performance. However, the authors reported training intensity as the key factor for performance improvements in highly-trained swimmers. This is somewhat in agreement with a recent review of Bishop, Granata and Eynon (2014) who examined the impact of training volume and intensity of exercise on mitochondrial content and function. Despite a lack of studies examining this phenomena, the major conclusions of this review suggested that training intensity is an important determinant of improvements in mitochondrial function but not mitochondrial content, and volume seems to be an important determinant in improvements in mitochondrial content but not function. Whilst both mitochondrial content and function are important to develop in order to increase the endurance

Chapter 2: Literature review

capacity of an athlete, this review also highlighted the fact that mitochondrial function might be a more important determinant of endurance performance than mitochondrial content. Whilst more studies are required to confirm what type of training maximises improvements in the content and function of mitochondria, these suggestions support the findings of Mujika et al. (1995); that intensity is a key factor in performance improvements in elite swimmers. Indeed, once swimmers reach an elite level, the volume completed by these athletes over years might have been sufficient to build adequate mitochondrial content, but there might still be a need to optimise training intensity to maximise the functional capacity of the large mitochondrial content these highly-trained individuals typically possess (Bishop, Granata and Eynon, 2014).

More recently, Faude et al. (2008) investigated the impact of high-volume, low-intensity and low-volume, high-intensity swim training in a randomised cross-over design in ten competitive swimmers for four weeks and found that none of the investigated parameters (i.e., anaerobic threshold, 100 and 400 m time trials) showed a significant interaction effect with any training type. The authors therefore concluded that a high-volume of low-intensity training has no advantage compared to high-intensity of low-volume training when implemented for four weeks. To summarise the findings currently available in this research area, Nugent et al. (2017) systematically reviewed the literature examining the effects of low-volume, high-intensity training strategy on performance in competitive swimmers and concluded that none of the seven eligible studies resulted in a reduction in physiological or swimming performance, and six and four out of these eligible studies resulted in improvements of physiological and swimming performance when this training strategy was implemented, respectively. The authors therefore postulated that higher intensity, lower volume training strategies could be an alternative for swimming training, whilst providing time for swimmers to focus on optimising technical and tactical skills, recovery, and to engage in activities outside of swimming to develop all round motor skills (Lloyd et al., 2015). Despite the positive findings from Nugent et al. (2017), the authors emphasised the limitations of the analysed studies. The limitations were related to the short duration of the study protocols (only three studies were >6.5 weeks), lack of swimming-specific methodologies, and lack of focus on obtaining a combination of physiological, biomechanical and swimming performance measures. Although longitudinal studies (>12 weeks) using more sport-specific methodologies

Chapter 2: Literature review

are needed to help to further the ‘Quality versus Quantity’ debate, based on the currently available evidence, an increase in volume might be appropriate as swimmers mature, however in highly-trained swimmers, a focus on optimising exercise intensity might be more appropriate as increases in training volume might ultimately lose the capacity to evoke desired adaptation (i.e., the ‘ceiling effect’), and instead increase a likelihood for overuse injury (Sein et al., 2010; Tovin, 2006), burnout (Raedeke et al., 2002) or overtraining (Meeusen et al., 2013).

Indeed, with taking over 2500 or more shoulder revolutions per day, the frequency of shoulder injury (the most common injury site) has been shown to strongly correlate with volume of swimming training, with swimmers that train more than 15 h.week⁻¹ and swim more than 35 km.week⁻¹ being two and four times more likely to suffer from shoulder pain and injury, respectively (Sein et al., 2010). Therefore, further research that explores alternatives to a high-volume training strategy for a longer period of time and utilising combinations of swimming-specific measures is required to provide coaches with suitable alternatives.

2.5 Exercise intensity domains

Exercise intensity can be described based on well-characterised profiles of physiological and metabolic responses elicited by ranges of work rates that separate the exercise intensity continuum into the exercise intensity domains (See **Figure 2.2**). It is now well established that the exercise intensity continuum comprises of four exercise intensity domains. Although the names of the exercise intensity domains can vary, the most commonly used terms to describe each domain in research are: moderate, heavy, severe, and extreme (Burnley and Jones, 2007). Each of these exercise intensity domains is demarcated by well-established physiological parameters and evoke distinct physiological responses to exercise, as evidenced through the behaviour of pulmonary oxygen uptake ($\dot{V}O_2$), blood acid-base status (blood lactate concentration [La⁻]) and neuromuscular responses (Jamnick et al., 2020; Black et al., 2017; Burnley and Jones, 2007; Reis et al., 2017; Pessoa Filho et al., 2012; Reis et al., 2012).

The moderate exercise intensity domain represents the work rates below the lactate threshold (LT) or gas exchange threshold (GET). Within this domain, there is no

Chapter 2: Literature review

change or only a transient increase in $[La^-]$ and $\dot{V}O_2$ attains a steady state within 2-3 minutes in healthy individuals (Burnley and Jones, 2007; Reis et al., 2017). In this domain, $\dot{V}O_2$ gain is highly predictable and corresponds to $\sim 10 \text{ mL O}_2 \cdot \text{min}^{-1} \cdot \text{W}^{-1}$. Moderate exercise can typically be continued for more than 4 hours, depending on the core temperature increase (hyperthermia), central fatigue, or muscle damage that are likely fatigue contributors in this domain. The lower boundary for heavy exercise intensity domain is demarcated by LT/GET. The upper boundary of the heavy exercise intensity domain is set by critical power (CP)/speed (CS) or maximal lactate steady state (MLSS), although other parameters such as lactate turnpoint (LTP), individual anaerobic threshold (IAT), onset of blood lactate accumulation (OBLA) or respiratory compensation point (RCP) have been utilised (Jamnick et al., 2020; Faude et al., 2009; Pessoa Filho et al., 2012; Reis et al., 2012; Fernandes et al., 2011). Exercise in the heavy domain is accompanied by elevated $[La^-]$ and development of a $\dot{V}O_2$ slow component that typically achieves a delayed steady state in ~ 10 -20 minutes, and $\dot{V}O_2$ gain may exceed $\sim 14 \text{ mL} \cdot \text{min}^{-1} \cdot \text{W}^{-1}$ (Burnley and Jones, 2007; Reis et al., 2012; Reis et al., 2017). The likely fatigue mechanisms in this domain are related to glycogen depletion and/or hyperthermia, and exercise in this domain can typically be performed up to ~ 3 -4 hours. The severe exercise intensity domain represents the work rates above CP/CS/MLSS but below the highest work rate that evokes $\dot{V}O_{2\text{MAX}}$ (Hill, Poole and Smith, 2002). In this domain a steady state in $[La^-]$ and $\dot{V}O_2$ can no longer be achieved (Pessoa Filho et al., 2012), and exercising in this domain is associated with development of the $\dot{V}O_2$ slow component and large disturbances in metabolic homeostasis, as evidenced through a decline in finite energy stores (muscle glycogen and [PCr] degradation), accumulation of fatiguing metabolites (e.g., inorganic phosphate $[P_i]$, hydrogen ions $[H^+]$) and ionic imbalance (potassium ions $[K^+]$ efflux) (Allen et al., 2008; Poole et al., 2016). This eventually drives $\dot{V}O_2$ to its maximum and exhaustion occurs soon thereafter, depending on the proximity of work rate to CS/CP (up to ~ 30 -45 min). The extreme exercise intensity domain is currently the highest defined intensity domain that represents the work rates at which fatigue and exhaustion ensues before $\dot{V}O_{2\text{MAX}}$ has been attained (Burnley and Jones, 2007; Hill, Poole and Smith, 2002). Time-to-exhaustion (TTE) in this domain is typically below 120 seconds as a result of [PCr] depletion, accumulation of fatiguing metabolites and excitation-contraction coupling failure (Burnley and Jones, 2007).

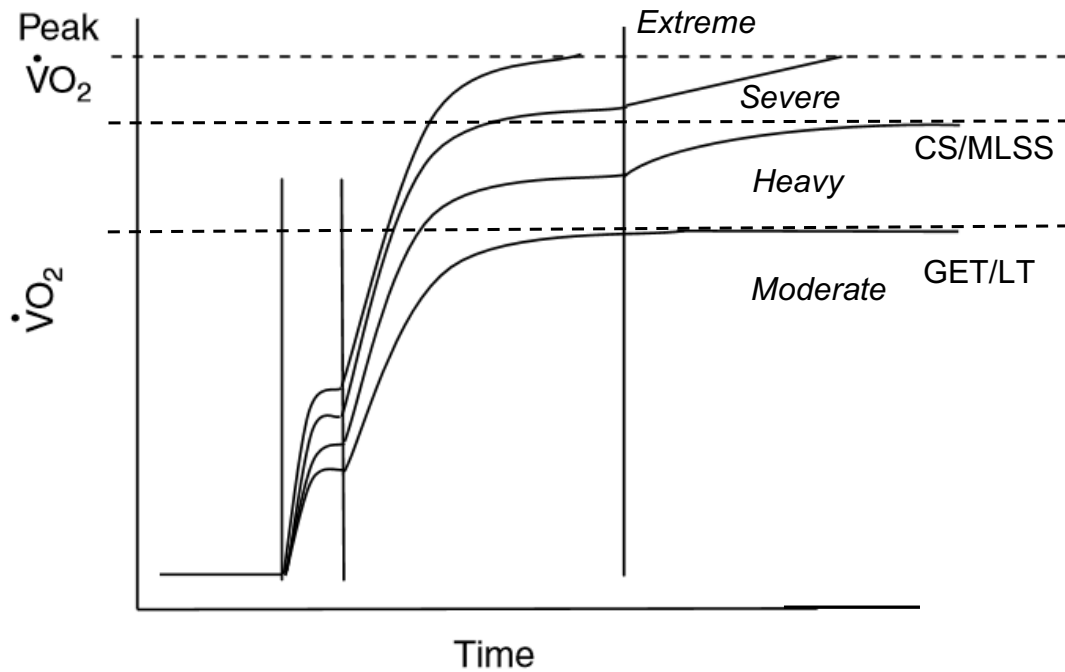


Figure 2.2. Responses of the oxygen uptake kinetics in the moderate, heavy, severe and extreme exercise intensity domains (Adapted from Fawcner & Armstrong, 2003).

Although the response profiles within the exercise intensity domains are consistent amongst individuals and modes of exercise, physiological parameters (i.e., ‘thresholds’ or ‘anchor points’) demarcating the exercise intensity domains vary between individuals (Jamnick et al., 2020; Burnley and Jones, 2007). Therefore, assessment of individuals’ physiological profiles becomes fundamental for the accurate prescription of exercise intensity (i.e. training) zones, individualised training, and monitoring of athlete’s progress. The accurate establishment of exercise intensity domains specific to an individual are especially important in swimming (Greco et al., 2013). Specifically, Greco et al. (2013) investigated the exercise intensity spectrum in trained swimmers and reported a very narrow range between the parameters demarcating the exercise intensity domains. Greco et al. (2013) not only found that the speed at LT occurred at the percentage of $\dot{V}O_{2MAX}$ similar to those reported in elite runners (i.e., 83%), but also found that there was a difference of only 0.06 m.s^{-1} ($\sim 5 \text{ s}$ per 100 m) between LT and MLSS speeds. The authors attributed this finding to the exponential relationship between the energy cost and speed as well as physiological

Chapter 2: Literature review

aspects specific to swimming (i.e., the horizontal position adopted, and hydrostatic pressure could enhance $[La^-]$ removal). Greco et al. (2013) therefore suggested that even slight over- or underestimation of LT or MLSS (<5%) could lead to unanticipated physiological responses, emphasising the need for more precise testing measurement of these transition thresholds in swimming practice.

2.6 Current testing methods in swimming research and practice

In order to obtain the aforementioned boundaries of exercise intensity domains, multiple approaches have been designed to demarcate one or all exercise intensity domains in swimming, each with their own strengths and weaknesses (Jamnick et al., 2020; Borresen and Lambert, 2009; Smith, Norris and Hogg, 2002). The incremental step test (IST) is perhaps one of the most utilised protocols in research studies examining the exercise intensity domains in swimming (Fernandes et al., 2008; 2011, Pyne, Lee, Swanwick, 2001). In this test swimmers are typically asked to complete 5-7 x 200 m with an increasing speed of 0.05 m.s^{-1} , or decreasing time by 5 s per stage whilst HR, $[La^-]$, rating of perceived exertion (RPE) and/or $\dot{V}O_2$ are collected and subsequently utilised to establish training zones. Although the ability of the IST to establish the boundary between heavy and severe domain of exercise has been questioned (Jamnick et al., 2018; Burnley, Doust and Vanhatalo, 2006; Dekerle et al., 2008), this test has been used for demarcation of all exercise intensity domains for decades.

To accurately establish the boundary between heavy and severe exercise intensity domains, the MLSS protocol is often considered as a gold standard method, although this has been recently questioned as well (Jamnick et al., 2020; Jones et al., 2019). The speed associated with MLSS is typically demarcated from a series (3-5) of exercise bouts performed up to 30 min in duration at constant intensity (speed), and is defined as the highest work rate at which $[La^-]$ increases by no more than 1 mmol.L^{-1} between 10th and 30th min of exercise (Beneke, 1995; Beneke and von Duvillard, 1996).

Despite these protocols being used by research studies to demarcate exercise intensity boundaries, these methods have not been used as extensively by the community of swimming coaches. This is likely due to the large amount of time, resources, and physiological expertise that these methods necessitate, which is often unavailable to

Chapter 2: Literature review

the majority of swimming coaches. Instead, a more common method utilised in swimming practice of coaches is to obtain individuals' HR_{MAX} , either via maximal exercise or predictive equations of '220-age' or '208-0.7 x age', which is subsequently utilised to prescribe 'beats below HR_{MAX} ' zones (BBM) for swimming training (see **Table 2.1**). Considering the inter- and intra-individual differences in the way athletes respond to exercise (Meyer et al., 1999), and that HR can vary by up to 3% (Bagger et al., 2003; Buchheit, 2014) or 6 bpm a day (Lambert et al., 1998) due to multiple factors (e.g. cardiac drift, sleep, temperature, hydration, nutrition) (Achten and Jeukendrup, 2003), using HR_{MAX} alone to optimise and prescribe training intensity for an individual athlete has been questioned (Jamnick et al., 2020; Meyer et al., 1999; Turner et al., 2008; Katch et al., 1978). Meyer et al. (1999) recruited thirty-six highly-trained cyclists and triathletes in order to assess the effectiveness of prescribing commonly used fixed percentages of maximal oxygen uptake (60 and 75% of $\dot{V}O_{2MAX}$) and maximal heart rate (70 and 85% of HR_{MAX}) compared to IAT. The authors demonstrated that when exercise at IAT is prescribed based on commonly fixed percentages of $\dot{V}O_{2MAX}$ or HR_{MAX} , wide ranges of exercise intensities were observed relative to IAT. These ranged from 86 to 118% for 75% of $\dot{V}O_{2MAX}$, and from 87 to 116% for 85% of HR_{MAX} . Also, work rates at 60% of $\dot{V}O_{2MAX}$ and 70% HR_{MAX} produced large ranges relative to IAT (66-91% and 53-85%, respectively). The low accuracy of the relative percent methods found by Meyer et al. (1999) is also in agreement with recent study of Weatherwax et al. (2019) who assessed changes in $\dot{V}O_{2MAX}$ values in response to standardised (based on % of heart rate reserve) and individualised (based on ventilatory thresholds) training programmes, which were prescribed 3 days a week for 12 weeks in 39 sedentary individuals. Although Weatherwax et al. (2019) found that both training interventions increased $\dot{V}O_{2MAX}$ values significantly, a significant difference in responsiveness was found between the individualised and standardised group, with 100% and 60% of participants categorised as responders, respectively. Although this study was conducted in sedentary population, the results emphasise the need for individualised prescription of training that might be even more important in athletes, whose capacity to improve is lower compared to sedentary population. Despite these findings, the accuracy of the BBM method has not been examined in swimming to date.

Chapter 2: Literature review

Alternatively to the method above, fixed values of $[La^-]$ for assessing LT (at 2 mmol.L⁻¹) and anaerobic threshold (at 3.5 or 4 mmol.L⁻¹) are still frequently utilised in swimming practice, despite the substantial evidence suggesting great inter-individual variability of $[La^-]$ kinetics, especially at anaerobic threshold (Jamnick et al., 2020; Fernandes et al., 2011; Tokmakidis et al., 1998). Indeed, Faude et al. (2009) suggested that using fixed values of $[La^-]$ may frequently result in underestimation (particularly in anaerobically trained swimmers) or overestimation (in aerobically trained) of anaerobic threshold speed.

Finally, personal best (PB+) times have been widely used in coaching practice to prescribe intensity zones, despite the fact that it is currently unclear as to what level of physiological intensity they represent, and the fact that athletes with equal PB might have different physiological profiles (Smith, Norris and Hogg, 2002). Given that applying fixed values of HR, $[La^-]$ or PB might result in prescription of training intensity below or above the parameters demarcating exercise intensity domains within and between athletes, using these methods can have significant implications on training prescription (Jamnick et al., 2020; Smith, Norris and Hogg, 2002; Burnley and Jones, 2007). Specifically, athletes supposedly undertaking identical training might in reality train either below or above LT and IAT, resulting in different physiological responses that can consequently be manifested in different training stimulus and ultimately adaptations. Therefore, there is clearly a need for protocols that allow coaches to accurately establish training zones but in a feasible way suitable to the restrictions they often operate under.

Chapter 2: Literature review

Table 2.1. Description and training intensity measurement utilised by swimming coaches, national training centres and delivered as a part of the swimming coaching curriculum in United Kingdom (Peyrebrune, 2005).

Training Zones	Name	Description	HR (bbm)	La (mM)	RPE
Zone 1	A1	<i>Aerobic Low Intensity</i> Base conditioning and technical training; warm-up and warm-down; Predominantly Fat Metabolism; largely slow-twitch fiber recruitment	> 50	< 2	< 9
	A2	<i>Aerobic Maintenance/ Development</i> Base aerobic training Improves cardio-respiratory system; enhances Lactate Removal	40-50	2-4	10-12
Zone 2	AT	<i>Anaerobic Threshold</i> Maximal Lactate Steady State where Lactate production = Lactate removal; Optimal intensity for development of aerobic capacity	20-30	3-6	14-15
Zone 3	VO ₂	<i>Aerobic Overload</i> High intensity work at approximately VO _{2max} ; This type of training includes Heart Rate and Vcrit sets; Improves VO _{2max} and aerobic power	5-20	6-12	17-19
Zone 4	LP	<i>Lactate Production</i> Training intensity results in the maximal speed of lactate build up This type of training includes Race Pace training Enhances rate of glycolytic energy production	5-15	8-15	17-19
	LT	<i>Lactate Tolerance</i> High intensity work with medium rest to improve buffering Developing the ability to tolerate lactate/ acidity in the muscle	0-10	12-20	19-20
Zone 5	Speed	<i>Sprinting –ATP-PC</i> High intensity, short duration, long rest repeats Designed to improve alactic energy production (ATP-PC), neuromuscular coordination and fast-twitch muscle fiber recruitment	N/A	N/A	N/A

bbm, beats below maximal heart rate of an individual; maximal heart rate is typically obtained via a maximal exercise, or equations: “220-age” Fox et al. (1971), “208-(0.7 x age)” Tanaka et al. (2001).

2.7 Speed-duration relationship and critical speed concept

Given the issues associated with using generalised but affordable methods on one end of the spectrum, and individualised but unfeasible methods on the other, Smith, Norris and Hogg (2002) suggested that performance itself may provide the best testing tool, as it encompasses the complex nature of sports performance. Certainly, aside from using performance data from competition, using maximal effort from time trials (TT) in training can be used to establish useful benchmark comparisons. Furthermore, these can be plotted to construct the speed (power)-duration relationship, which was first demonstrated by the Nobel Prize winner A.V.Hill from world records of runners, swimmers, rowers, and cyclists in 1925 (Hill, 1925). Since the first demonstration of the speed-duration relationship, this relationship has become one of the fundamental tenets of exercise physiology and has been applied across multiple modes of exercise, including swimming (Wakayoshi et al., 1992a; 1992b; 1993; Burnley and Jones, 2018). The speed-duration relationship has also been demonstrated across a spectrum of conditioning levels, from elite athletes (Jones and Vanhatalo, 2017) to patient populations (Neder et al., 2000).

Since A.V. Hill's first demonstration of the speed-duration relationship, this relationship has also been described mathematically and has provided a base for the critical power (speed) concept established by Monod and Scherrer in 1965 (Monod and Scherrer, 1965). Monod and Scherrer (1965) demonstrated that there was a linear relationship when the total work done was plotted against time-to-exhaustion (TTE) for multiple bouts of dynamic, isometric and intermittent isometric exercise performed using different isolated muscle and muscle groups. Consequently, Monod and Scherrer (1965) defined the two parameters of this relationship as 'threshold of local fatigue' and 'energetic reserve', which were later termed as critical power (CP) (or critical speed [CS] when intensity is measured in units of speed), and the finite work capacity above CP known as W' (W prime, measured in units of work done, that is, joules) (or D' when measured in units of distance, that is, meters), respectively. The CS concept describes the limits of high intensity (i.e., severe) exercise performance via the demarcation of two physiological parameters; critical speed (CS) and the finite work capacity above critical speed (D'), often referred to as "fatigue threshold" and "fatigability constant", respectively (Poole et al., 2016). Whilst CS represents the highest speed that can be maintained for an extended period of time via mostly aerobic

Chapter 2: Literature review

energy supply (~20-60 minutes), the capacity to exercise above CS (i.e., D') is finite and highly predictable. Whilst CS/CP is a relatively well defined and reliable parameter (typical coefficient of variation [CV] of 1-7%), W'/D' is less reliable (CV of 5-21%) and has been often mistakenly characterised as solely an anaerobic energy store. The characterisation of W'/D' has been redefined recently, suggesting that W'/D' is not determined by intramuscular stores of [PCr], glycogen, ATP and limited O₂ stores only, but is also linked to the $\dot{V}O_2$ slow component and fatigue inducing metabolites (e.g., [H⁺], [P_i], ADP, extracellular [K⁺]) (Jones et al., 2010; Poole et al., 2016). Most swimming events last between ~1-20 min and are performed in the severe exercise intensity domain. As such, the CS concept is highly applicable for swimming races and training, in which swimmers aim to maintain and develop their highest sustainable speed, respectively (Pyne and Sharp, 2014; Smith, Norris and Hogg, 2002) and can provide information on both aerobic and anaerobic capacities of a swimmer. It is however important to note that given the differences in bioenergetics (e.g., slower $\dot{V}O_2$ on-kinetics in swimming, greater energy cost of movement) between swimming and land-based sports mentioned earlier (Sousa et al., 2015a,b, section "The unique characteristics of swimming"), this could have implications on the speed-duration relationship and consequently CS and D' values derived.

Dekerle et al. (2005b; 2002), Barden and Kell (2009), Franken et al. (2013) and Pelarigo et al. (2016) recently demonstrated that MLSS and CS do not only represent a physiological boundary between the heavy and severe domains of exercise, but also a biomechanical threshold beyond which stroke mechanics, namely stroke length, becomes compromised, making this concept a very interesting area to explore and apply in swimming. To extend the utility of the CS concept, Dekerle et al. (2002) introduced a biomechanical surrogate of the CS concept; the critical stroke rate (CSR). Akin to CS, CSR represents the highest SR that can be maintained for an extended period of time. Dekerle et al. (2002) and Franken et al. (2013) demonstrated that there is a direct link between CSR and CS, as the recruited swimmers spontaneously adopted CSR when asked to swim at CS, and vice versa. Indeed, using the idea of 'double task constraint' strategy (i.e., imposed speed and SR) described earlier, Dekerle et al. (2002) advised constructing training sessions with the aim to swim at CS but with the SR < CSR, thus requiring swimmers to adopt and maintain longer stroke length (SL), either through application of greater force or the improved efficiency with which the

Chapter 2: Literature review

force is applied on to the water. Despite Dekerle's et al. (2002) suggestions, the impact of this training strategy on parameters of swimming technical efficiency has not been investigated to date.

There is also accumulating evidence that the CS concept is a stronger predictor and a more meaningful parameter for sports performance than LT and/or $\dot{V}O_{2MAX}$, as it provides parameters that have direct implications for fatigue, training and performance processes (Vanhatalo, Jones, and Burnley, 2011; Jones et al., 2010; Pettitt, 2016; Morgan et al., 2018). Yet, it is important to note that applying the CP/CS concept requires consideration of the following assumptions (Dekerle et al., 2006; Morton, 2006); 1) There are only two components to the energy supply for exercise, aerobic and anaerobic; 2) The aerobic energy supply is unlimited in capacity but is limited in rate (CP/CS); 3) The anaerobic energy supply is unlimited in rate but is limited in capacity (W'/D'); 4) Exhaustion occurs when all W'/D' has been utilised; 5) $\dot{V}O_{2MAX}$ is achieved at the beginning of the exercise; 6) The work rate over which the model applies is $CP/CS < \infty$; 7) The time over which the model applies is infinitely long when exercising at CP/CS; 8) The energy cost of activity is constant; and 9) CP/CS and W'/D' are constants, independent of work rate and/or time. As our knowledge of human bioenergetics has developed substantially since the seminal study of Monod and Scherrer (1965), these assumptions have since been questioned (Morton, 2006). Despite this, it should be noted that when appropriate procedures are applied, the CS concept is still considered to provide useful information to researchers and practitioners alike (Jones et al., 2010).

2.7.1 Conventional protocol to estimate CS concept parameters

To establish the parameters of the CS concept, a wide range of trials have been utilised in previous research studies (~1-30 min), mostly adopting a ~2-15 minutes duration range (Triska et al., 2018). Given that attaining $\dot{V}O_{2MAX}$ and utilising D' at the end of each exhaustive trial is a prerequisite for optimal determination of the speed-duration relationship (di Prampero, 1999), the implementation of trials shorter than 2 min and longer than 15-20 min have been discouraged by numerous researchers (Dekerle et al., 2002; Bergstrom et al., 2017; Vandewalle et al., 1997). Specifically, in trials shorter than 2 min, $\dot{V}O_{2MAX}$ might not be attained and D' might not be fully utilised (Hill, Poole and Smith, 2002; Di Prampero, 1999). Conversely, due to motivational,

Chapter 2: Literature review

nutritional and temperature factors, as well as the exercise intensity being too low despite being performed in the severe domain, $\dot{V}O_{2MAX}$ might not be attained in the trials longer than 15 min (Bergstrom et al., 2017; Sawyer et al., 2012; Vandewalle et al., 1997). Additionally, whilst trials shorter than ~2 min generally tend to overestimate CS and underestimate D', longer trials have a tendency to underestimate CS and overestimate D' (Vandewalle et al., 1997; Dekerle et al., 2002). As such, the general consensus for the method of best practice has been to complete a minimum of three maximal effort trials lasting ~2-15 min, with a minimum of a 5 min difference between the shortest and the longest trial (Triska et al., 2018; Housh et al., 1990). Although the use of time trials (TT) as opposed to time-to-exhaustion (TTE) trials has been under debate recently, the trials can be performed at either set power output or speed with variable TTE or at set time or distance with variable speed or power output (Triska et al., 2017; Coakley and Passfield, 2018; Karsten et al., 2018). These are consequently used to define CS and D' via a hyperbolic relationship or linear regression (**Figure 2.3**). In the hyperbolic speed-duration model, time (x-axis) is plotted against speed (y-axis), with the speed-asymptote representing CS and the curvature constant of this relationship representing D' (Pettitt, 2012; Vanhatalo, Jones and Burnley, 2011). Alternatively, the hyperbolic speed-duration relationship can be transformed into a linear distance-time or speed-inverse-of-time relationships by plotting distance and speed (y-axis) relative to time and inverse-of-time (x-axis), respectively. Subsequently, linear regression is used to determine CS and D', which are represented by the slope and y-intercept in the distance-time model, respectively; this is reversed in the speed-inverse time model (CS= y-intercept; D'= slope) (Pettitt, 2012; Mondon and Scherrer 1965).

Chapter 2: Literature review

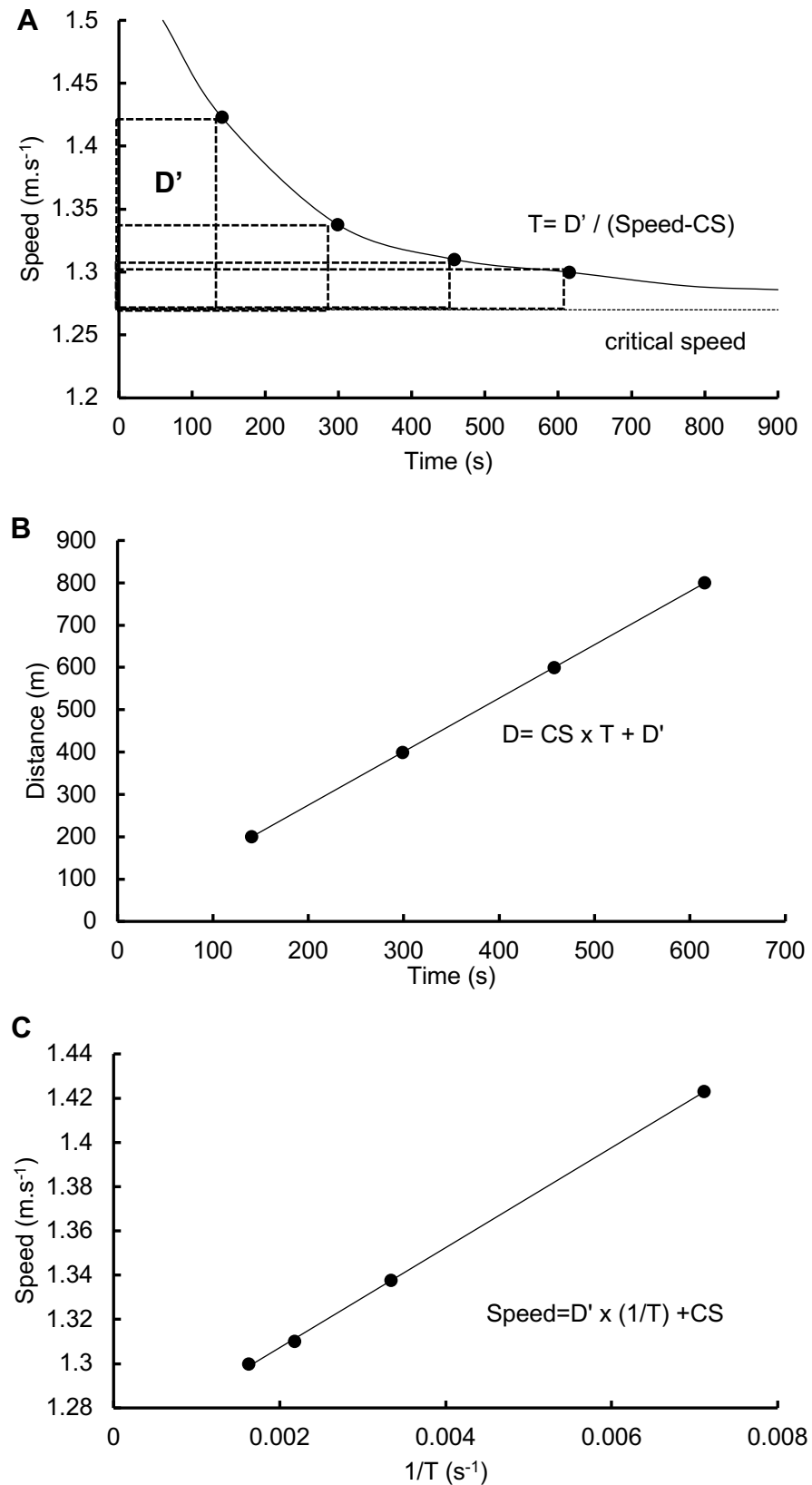


Figure 2.3. Calculation of the critical speed (CS) and finite work capacity above CS (D') using (A) hyperbolic speed-time, (B) distance-time and (C) speed-inverse time ($1/T$) relationships; D , distance; T , time.

Chapter 2: Literature review

2.7.2 CS as the transition threshold between heavy-severe exercise

Although the CS concept has been studied for decades in one form or another, some of the key features of this concept have only come to light relatively recently. Firstly, a number of studies have provided evidence that CP/CS demarcates the boundary between heavy and severe exercise intensity domains ($\sim 70\text{-}90\%$ of $\dot{V}O_{2\text{MAX}}$ depending on a training status, or $\sim 50\%$ Δ), and occurs at a similar work rate corresponding to MLSS (Poole et al., 1988; Jones et al., 2008; Wakayoshi et al., 1993). Poole et al. (1988) was amongst the first studies to identify CP as the highest work rate that can be maintained without progressive loss of homeostasis, as evidenced through $\dot{V}O_2$ and $[La^-]$ that stabilised within several minutes of exercise at CP. Conversely, when power output was set at 5% above CP, the authors observed continued rise in $\dot{V}O_2$ towards $\dot{V}O_{2\text{MAX}}$ and $[La^-]$ until the subjects reached exhaustion. To verify the position of CP at the intramuscular level, Jones et al. (2008) used ^{31}P -magnetic resonance spectroscopy to monitor $[PCr]$, pH, and $[P_i]$ responses during knee-extension exercise at 10% below and above CP. The steady-state responses in $[PCr]$, $[P_i]$ and pH were achieved within 3 min and all subjects completed 20 min of exercise at 10% below CP. In contrast, the levels of $[PCr]$ and pH continuously declined and $[P_i]$ increased when exercise was performed at 10% above CP, reaching exhaustion at ~ 14.7 min. Evidence from these studies have consequently led to the suggestions that CP/CS represents the highest rate of oxidative metabolism that can be maintained without increasing contribution from substrate-level phosphorylation and progressive accumulation of fatiguing metabolites (Jones et al., 2010; Black et al., 2017; Poole et al., 1988, Jones et al., 2008).

Despite these findings, a number of studies recently questioned whether CS/CP corresponds to MLSS. Accumulating evidence suggests that CS might occur at higher work rate than MLSS ($\sim 5\text{-}6\%$), and exercising at CS/CP continuously can elicit non-steady state responses in $\dot{V}O_2$ and/or $[La^-]$ (Dekerle et al., 2003; 2005a; 2010; Smith and Jones, 2001; Pringle and Jones, 2002; Brickley, Doust, Williams, 2002; Mattioni Maturana et al., 2016). Wakayoshi et al. (1992a; b; 1993) were the first to apply the CS concept in swimming, and examined the relationship between CS and MLSS. Wakayoshi et al. (1993) found that when eight well-trained swimmers were asked to swim at CS in 4 x 400 m with 30-45 s rest to obtain blood samples, the swimmers

Chapter 2: Literature review

were able to sustain the CS with steady state levels of $[La^-]$. In contrast, when swimmers swam at the speed corresponding to 102% of CS, $[La^-]$ levels continued to rise. Dekerle et al. (2005a) questioned the impact of the rest duration on this finding, suggesting that the rest period allowed greater removal of $[La^-]$ via oxidation. Dekerle et al. (2005a) therefore compared CS with the direct method of assessing MLSS described earlier. The authors found that CS was significantly higher than the speed associated with MLSS ($\sim 5.6\%$). The authors also suggested that swimming at CS would be accompanied with a continuous increase in the $[La^-]$, as the constant speed test at 90% of maximal aerobic speed (MAS) utilised to establish MLSS was accompanied by non-steady state in $[La^-]$ levels and was similar to the CS work rate ($92.7 \pm 2.6\%$ of MAS). The important limitation of this study, as acknowledged by the authors, was the implementation of trials in the range of 1.6-7.1 min that could have led to overestimation of the CS, and therefore the results were not conclusive. To investigate this further, with both pulmonary $\dot{V}O_2$ and $[La^-]$ as well as a wider TT range (i.e., 1-10 min), Dekerle et al. (2010) examined the physiological responses of nine well-trained swimmers swimming at 5% above and below CS as well as at CS during continuous and intermittent swimming. The major findings from this study implied that when swimming continuously at 5% above and below CS, similar responses characterising those of severe and heavy domain of exercise, respectively, were observed. However, when the swimmers were asked to swim continuously at CS, a TTE of 24 ± 8 min (14.3-39.4 min) was observed alongside $[La^-]$ that continued to increase from the 10th min towards the end of the test where 95% of peak $\dot{V}O_2$ was reached. Yet, when the swimmers were asked to swim at CS in blocks of 400 m with ~ 40 s rest, the same intensity was maintained for longer (10 x 400 m, ~ 50 min) and with steady state levels of $[La^-]$, similar to Wakayoshi et al. (1993). This is in agreement with Zacca et al. (2016), who recently observed steady state responses in $\dot{V}O_2$, $[La^-]$ and HR when ten well-trained swimmers were asked to swim at CS in 3 x 10 min blocks with 45 s rest in-between. In agreement with Dekerle et al. (2010), de Lucas et al. (2012) compared the speed obtained from MLSS continuous and intermittent protocols (5 min run, 1 min rest) with CS in eight national endurance runners and found that whilst the speed from a continuous MLSS protocol (14.4 ± 0.6 km.h⁻¹) was 5.6% lower compared to CS (15.2 ± 1 km.h⁻¹), the speed from an intermittent MLSS protocol (15.3 ± 0.7 km.h⁻¹) was not significantly different and

Chapter 2: Literature review

correlated significantly with CS ($r=0.84$). Interestingly, the typically observed differences between CS and MLSS derived from the continuous protocol seems to coincide with the differences often observed between the MLSS derived from continuous and intermittent protocols (4% in swimming [Oliveira et al., 2012], 8% in cycling [Beneke et al., 2003], and 6% in running [De Lucas et al., 2012]). These data possibly imply that CS might correspond better to the MLSS determined from an intermittent protocol, which has been shown to allow swimmers to swim at ~4% higher speed with similar $[La^-]$ responses and to maintain better technical efficiency compared to those observed at MLSS derived from a continuous protocol. Considering the findings from Dekerle et al. (2010) and de Lucas et al. (2012), the fact that the sustainable range of CS fits well with competitive events of swimming, and that training is typically prescribed in an intermittent fashion (i.e., work and rest intervals), the CS concept is a meaningful, low-cost, and non-invasive tool for assessing the boundary between heavy and severe exercise intensity domains, and training prescription in applied practice.

2.7.3 Factors effecting the estimation of the CS concept parameters

Whilst the equivalence of CS to MLSS has been recently questioned by the aforementioned studies, Keir et al. (2017) and De Lucas (2018) provided interesting editorials in which very important points were made. Whilst De Lucas (2018) questioned whether there is still a need to compare CS and MLSS due to the inherent differences between protocols and published findings, Keir et al. (2017) specifically questioned whether the true CS/CP was derived in the previous studies comparing CS/CP to MLSS, as the authors acknowledged the sensitivity of the CP/CS concept to the protocol utilised as well as a lack of validation of physiological ($[La^-]$ / $\dot{V}O_2$) and TTE responses when exercising at derived CS/CP. Indeed, accumulating evidence suggests that the traditional determination of CS/CP and D'/W' is protocol dependent, as it is influenced by duration and number of intervals (Triska et al., 2018, Mattioni Maturana et al., 2018 Zacca et al., 2010), mathematical model applied (Mattioni Maturana et al., 2018; Jones et al., 2010; Bull et al. 2000; Gaesser et al., 1995; Tsai and Thomas, 2017, Bergstrom et al., 2014; Zacca et al., 2010), implementation of familiarisation trials (Triska et al., 2017; Parker Simpson and Kordi, 2017) and inter-trial recovery duration (Karsten et al., 2017; Karsten et al., 2018).

Chapter 2: Literature review

More recently, Mattioni Maturana et al. (2018) investigated how different protocols and models affect the determination of the CP concept parameters in thirteen highly-trained cyclists. The 2 and 3-parameter hyperbolic, linear and linear 1/time models using different numbers and combinations of TTE trials (1-20 min) were used for CP and W' estimations and were compared to the criterion method (3-parameter hyperbolic model with 5 trials). The results indicated that, for a given set of data points, different estimations were yielded by the various models, consistent with previous research studies (Jones et al., 2010; Bull et al., 2000; Gaesser et al., 1995; Tsai and Thomas, 2017; Zacca et al., 2010). The CP was considerably overestimated and W' was considerably underestimated when only trials <10 min were used, independent of the model employed. However, when longer TTE trials (12-20 min) were included, the estimations for CP and W' became closer to the criterion method. The authors concluded that the 3-parameter model provides the most accurate estimates, but suggested that accurate estimations can be made with more time-efficient models using simpler analyses (e.g. linear, linear 1/time) if TTE trials ranging from 7-20 min are included in these models.

To shed more light on the impact of interval duration of trials on CS and D' estimates, Triska et al. (2018) compared two protocols using different exhaustive times but both within currently recommended 'best practice' methods in ten national and international triathletes (Protocol 1: 12, 7, 3 min vs Protocol 2: 10, 5, 2 min). Although the methods of best practice were employed, differences in CS and D' between protocols were observed (Protocol 1, CS: $4.17 \pm 0.37 \text{ m.s}^{-1}$, D': $144.8 \pm 29.6 \text{ m}$; Protocol 2, CS: $4.29 \pm 0.30 \text{ m.s}^{-1}$, D': $124.4 \pm 25 \text{ m}$), suggesting the protocols should not be used interchangeably. Additionally, the same research group recently assessed the reliability of CP parameters in highly-trained cyclists and recommended implementing familiarisation with the trials used for determination of the CP and W' in order to derive these values optimally (Triska et al., 2017). Indeed, Triska et al. (2017) found that even though their participants were familiar with TT efforts in the field, they produced lower CP estimates ($\sim 3.5\%$) and substantially higher W' estimates ($\sim 13\%$) when familiarisation trials were not performed. However, following the completion of familiarisation trials, the authors observed a reduction in standard error of the estimate (SEE) by $\sim 30\%$ (CP) and by $\sim 50\%$ (W'), and in CV by 1.5% (CP) and 17.1% (W'). This was also confirmed in the study of Parker Simpson and Kordi

Chapter 2: Literature review

(2017), who suggested that even highly-trained cyclists appear to need two familiarisation trials when using fixed duration TT in laboratory settings, as evidenced with ~5% lower CP values in sessions 1 and 2 compared to subsequent sessions.

In order to reduce the time-consuming nature of the traditional method of determining CS/CP and D'/W', multiple research studies tested the possibility of assessing these estimates in one day by reducing the duration of the inter-trial recovery from 24 hours to 3 hours or 30 min (Galbraith et al., 2014; Bishop and Jenkins, 1995; Karsten et al., 2017). Since shorter inter-trial recovery time might not allow full restoration of D'/W' (Ferguson et al., 2010) and might lead to primed $\dot{V}O_2$ kinetics and performance enhancements (Bailey et al., 2009), Karsten et al. (2017) compared estimates of CP and W' derived using 24 h, 3 h and 30 min inter-trial recovery period in trained cyclists. The results from this study indicated an acceptable level of agreement and low prediction error for CP using 30 min and 3 hours inter-trial recovery period (<4%), however, this was not transferable to W', which showed an unacceptably low level of agreement and high prediction error (~30%) for both testing protocols. Contrastingly, this research group have since shown that 30-min inter-trial recovery between 10, 5, and 2 min TT can be used to determine both CP and W' accurately in triathletes (Triska et al., 2020).

Finally, previous research has noted the sensitivity of CS/CP and D'/W' to prior exercise in the heavy (Clark et al., 2018) and severe exercise intensity domains (Ferguson et al., 2007; Vanhatalo and Jones, 2009; Parker Simpson et al., 2012), hypoxia (Townsend et al., 2017; Parker Simpson et al., 2015; Dekerle, Mucci and Carter, 2012), hyperoxia (Vanhatalo et al., 2010), glycogen availability (Miura et al., 2000), creatine, caffeine and bicarbonate supplementation (Miura et al., 1999; Kendall et al., 2009; Silveira et al., 2017; Deb et al., 2017), cadence (Vanhatalo, Doust, and Burnley, 2008b) and mental fatigue (Salam et al., 2018). Therefore, to optimally derive CS/CP and D'/W', practitioners are recommended to minimise inconsistency in warming up and environmental factors as well as the nutritional and psychological status of athletes between trials.

Chapter 2: Literature review

2.7.4 Application of the CS concept to all-out exercise

Although the traditional CS models have been applied in multiple sports and numerous attempts have been made to reduce their time-consuming nature, there has been a consistent need for more ecologically valid testing protocols. Indeed, Jones et al. (2010) suggested that the cumbersome nature of the traditional protocol might be a factor that has prevented the wider application of the CS/CP concept, despite its broad applicability. To address this, an all-out exercise test was considered based on the principle of the power-duration relationship (i.e., the early part of the test would deplete W' / D' , therefore the highest possible work rate at the end of the test should equal to CP/CS). To investigate this concept, Brickley et al. (2007), applied a 90 s all-out cycling test in sixteen active individuals. The results of this study indicated that $\dot{V}O_{2peak}$ at the end of the 90 s all-out test was not achieved (i.e., 88% of $\dot{V}O_{2MAX}$ from a ramp test), which was in contrast to Williams, Ratel and Armstrong (2005) who observed similar $\dot{V}O_{2peak}$ values yielded by 90 s all-out test and a ramp test in adolescents. Additionally, Brickley et al. (2007) found that the power output at the end of the all-out test was ~10% higher than individuals' CP (292 ± 65 W vs. 264 ± 50 W, respectively). Therefore, the authors postulated that a test with longer duration would allow attainment of $\dot{V}O_{2MAX}$ and identification of CP. To investigate this further, Burnley, Doust and Vanhatalo (2006) suggested a 3-min all-out test (3MT) to identify CP and $\dot{V}O_{2peak}$. This was the first study to demonstrate that during an all-out exercise test, work rate gradually declined and stabilised towards the end of the test to a power output that could represent MLSS or CP. Indeed, when the subjects were asked to exercise at 15 W below the end-power attained in the last 30 s of the 3MT, nine out of eleven subjects completed 30 min of this exercise, and seven out of these did so with steady state responses in $[La^-]$ and $\dot{V}O_2$. Conversely, when exercise was performed at 15 W above the end power from 3MT, $[La^-]$ and $\dot{V}O_2$ progressively increased until exhaustion occurred in 13 ± 7 min. Vanhatalo, Doust and Burnley (2007) then compared CP and W' estimates from the conventional method (5 trials, with a 2-15 min TTE range) with those derived from 3MT. The authors found no significant differences (CP: 287 ± 56 W vs 287 ± 55 W; W' : 16 ± 3.8 kJ vs 15 ± 4.7 kJ), and a close agreement between the estimates derived from the two methods ($r=0.99$ for CS, $r=0.84$ for W'), suggesting that the 3MT could be used as an alternative protocol to assess CP and W' . The 3MT requires an athlete to exercise in an 'all-out' effort for

Chapter 2: Literature review

180 s, which is sufficient to fully deplete their D'/W' within 150 s, resulting in an average speed or power output for the final 30 s that corresponds to CS/CP, respectively (Vanhatalo, Doust and Burnley 2007, Francis et al., 2010). Since the seminal work of Burnley, Doust and Vanhatalo et al. (2006) multiple studies have assessed the validity and applicability of the 3MT compared to conventional protocols in multiple modes and contexts of exercise, such as cycling (Pettitt et al., 2015; Black et al., 2014; Vanhatalo, Doust and Burnley, 2007; Bartram et al., 2016; Bergstrom et al., 2014), running (De Aguiar et al., 2018; Broxterman et al., 2013; Pettitt, Jamnick and Clark, 2012), rowing (Cheng et al., 2012), swimming (Tsai and Thomas, 2017), soccer (Clark et al., 2013; Kramer et al., 2018b), rugby (Kramer et al., 2018a; Kramer et al., 2019), military special forces (Dicks et al., 2018; Hoffman et al., 2016), shuttle running (Saari et al., 2019), arm crank (Flueck et al., 2015), and knee extension exercise (Burnley, 2009), with some suggesting a close agreement between methods whilst others suggesting that 3MT overestimates CS/CP and underestimates or overestimates D'/W' .

2.7.5 Application of the CS concept and 3MT in sports performance

Since the emergence of the 3MT, considerable advancements to the CS/CP concept have taken place, including further understanding of the methodology behind the CS concept and parameters itself, as well as its further application in applied practice. One of the main applications of the CS concept that has recently received attention is the prescription and evaluation of personalised high intensity interval training (HIIT). HIIT is often prescribed as a percentage of minimum velocity eliciting maximum oxygen uptake ($v\dot{V}O_{2MAX}$) or HR_{MAX} . However, these methods do not take into account the between-subject differences in aerobic or anaerobic capacity. Specifically, two athletes with identical $v\dot{V}O_{2MAX}/HR_{MAX}$ might have divergent anaerobic capacities to work above CS, and therefore the prescription of a supposedly identical HIIT session may in reality lead to different physiological responses and exercise tolerance (Buchheit and Laursen, 2013). The CS concept provides a solution to this problem; firstly, CS represents the lower boundary of exercise required to evoke $\dot{V}O_{2MAX}$; secondly, the CS concept also identifies a value of D' , representing an indirect measure of anaerobic capacity. The advantage of utilising CS and D' in prescription of HIIT is that time intervals for a given distance or speed are based on a fractional depletion of D' (% D'), relative to an athlete's CS, meaning that HIIT is personalised

Chapter 2: Literature review

to the individual's aerobic and anaerobic capacity. Indeed, Clark et al. (2013) and Courtright et al. (2016) demonstrated that when CS and D' derived from 3MT were utilised to prescribe personalised HIIT (2 days.week⁻¹) for four weeks in competitive soccer players and swimmers, respectively, significantly improved CS, average velocity for the first 150 s, and total distance covered in 3MT were observed. This was somewhat surprising given the low volume of HIIT prescribed (i.e., 900-3000 yards.week⁻¹; 40-60 min.week⁻¹ in Courtright et al., 2016). This suggests that this approach may be a viable alternative to the high-volume strategies typically employed in swimming.

Accumulating evidence suggests that the prescription of HIIT based on 5 x 60, 4 x 70 and 3 x 80% of D' with interval duration of 2-5 min and with a work to rest ratio of 1:1 (for 60-70% of D') or 1:1.5 (for 80% of D') tends to favour gains in CS and $\dot{V}O_{2MAX}$ (Pettitt, 2016; Clark et al., 2013; Courtright et al., 2016; Pettitt et al., 2015). The optimal interval durations to elicit gains in D' are currently unclear, but are suggested to be less than 2 min, which might need to be prescribed at intensity exceeding 130% of $\dot{V}O_{2MAX}$ (Pettitt, 2016; Clark et al., 2013). Despite these positive findings, studies with longer intervention periods are required to elucidate whether this method of prescribing HIIT is effective in eliciting continual improvements in performance or was only observed as a result of a reduction in volume and increase in intensity (as typically prescribed during a taper).

The CS concept and 3MT has also found its application in other areas of sports performance such as in prediction of performances, in assisting with development of optimal warm ups, racing and pacing strategies, and doping detection (Pettitt, 2016; Jones et al., 2010; Puchowicz et al., 2018). Indeed, by knowing the CS and D' of an individual athlete, a practitioner is able to predict the time within which a given athlete is capable of completing a specific distance (D) using the **Equation 2.1**:

Equation 2.1.

$$\text{Time} = (D - D') / \text{CS}$$

Additionally, a practitioner is also able to establish what speed (S) an athlete can maintain or how much distance one can cover for a given time by using **Equation 2.2** and **Equation 2.3**:

Chapter 2: Literature review

Equation 2.2.

$$D = (CS \times \text{time}) + D'$$

Equation 2.3.

$$S = D'/\text{time} + CS$$

Finally, to extend the utility of the 3MT, Francis et al. (2010) utilised the CP from the 3MT to approximate the boundary between moderate-heavy and severe-extreme exercise intensity domains in competitive cyclists. Specifically, by using linear regression through the origin analysis between CS and LT, and CS and power output associated with $\dot{V}O_{2\text{peak}}$ derived from an IST, Francis et al. (2010) approximated LT and power output associated with $\dot{V}O_{2\text{peak}}$ at 76% and 105% of CP, respectively, and suggested that CP derived from 3MT can be used as an alternative to IST to establish boundaries of exercise intensity domains if practitioners are working in resource, time, or expertise limited environments.

2.7.6 Application of the 3MT in swimming

Despite the promising application and complex but non-invasive assessment of performance the 3MT and CS concept could provide to swimming practice, these concepts have not been extensively studied and utilised in swimming. To date, only two attempts have been made to assess validity of the 3MT in free swimming (Tsai and Thomas, 2017; Mitchell et al., 2018a). Tsai and Thomas (2017) examined the validity of the 3MT in ten recreational swimmers and triathletes and found that D' derived from the 3MT was lower compared to conventional distance-time and speed-inverse time methods (17.51 ± 7.54 m vs. 29.23 ± 6.42 m and 23.13 ± 4.94 m) whilst CS derived from this test (0.91 ± 0.13 m.s⁻¹) was not different compared to the distance-time model (0.92 ± 0.14 m.s⁻¹) but was significantly different compared to speed-inverse time model (0.94 ± 0.13 m.s⁻¹). Mitchell et al. (2018a) assessed the validity of a modified 3MT (12 x 25 m) in national and international swimmers, and found that CS derived from the modified 3MT (1.49 ± 0.17 m.s⁻¹) was significantly higher compared to the CS derived from two TT (1.43 ± 0.15 m.s⁻¹). Whilst Mitchell et al. (2018a) found no significant difference between D' values derived from the modified 3MT and TT (16.2 ± 6.3 m vs 14.9 ± 3.4 m), the result for D' did not display a sufficient level of agreement. However, both of these studies were subject to a number of

Chapter 2: Literature review

potential limitations: Tsai and Thomas (2017) used a recreational, less technically proficient and heterogeneous sample of athletes; combined primary (TT using a push-off start) and secondary data (race results using a dive start) for derivation of CS and D' in the conventional methods; used an inconsistent and high-intensity warm-up protocol; and failed to implement a familiarisation with 3MT. Mitchell et al. (2018a) used only two TTs (100 and 200 m) that were obtained from short or long course races (using a dive start and turns), both with a duration $< \sim 2.5$ min; excluded turns from the 3MT; and allowed ~ 5 s rest between each 25 m push off. The aforementioned factors may have impacted on the results, given the previous research demonstrating the impact of these factors on derivation of CS/CP and D'/W' discussed earlier (Jones et al., 2010; Ferguson et al., 2010; Triska et al., 2017; Dekerle et al., 2002; Tsai and Thomas, 2017). Accordingly, to date, no study has assessed the validity and reliability of the continuous 3MT in highly-trained swimmers. Equally, the broad applicability of the CS concept and this test has not been fully explored in swimming research and practice. As physiological testing and the prescription of individualised training can be especially challenging in swimming due to the aforementioned environmental and technological constraints, as well as the multidisciplinary nature of swimming, the 3MT and CS concept represent promising tools that have the potential to allow complex assessments of large groups of swimmers and individualised prescription of training on a regular basis with minimal resources, time and expertise (Vanhatalo, Jones and Burnley, 2011). This test could therefore help to 'close the gap' between science and practice which currently exists in testing and prescription of personalised training in swimming (Roos et al., 2013; Buchheit, 2017).

2.8 Monitoring athletes' status

Whilst accurate demarcation of exercise intensity domains and its subsequent use for individualised training prescription are critical components of effective training programmes, monitoring of training load and responses of athletes to this training load are equally important. In general, the main purpose of monitoring is to assess the preparedness of athletes to complete the designed training and monitor their progress, with the overriding aim being to avoid illness, injury and overtraining, as well as to assist short-term and long-term planning. Indeed, athlete monitoring has been implemented by coaches and sports practitioners in one form or another for decades (Borresen and Lambert, 2009; Halson, 2014). Nowadays, multiple monitoring tools

Chapter 2: Literature review

exist and are available to sports practitioners (Feijen et al., 2020; Smith, Norris and Hogg, 2002). Despite the recent growth in the literature examining the area of athlete monitoring, the amount of resources, time and level of expertise required to regularly obtain and handle the data by coaches and other sports practitioners are still common factors that prevent the translation of science into practice in this area as well (Roos et al., 2013; Halperin, 2018; Buchheit, 2017; Neupert, Cotterill and Jobson, 2018).

2.8.1 Session of Rating of Perceived Exertion

Considering the restrictions within which most of the practitioners often have to work in, there is no surprise that one of the most utilised monitoring tools in swimming practice has been session Rating of Perceived Exertion (sRPE), originally proposed by Carl Foster in 1998 (Foster, 1998; Wallace et al., 2008). The sRPE accounts for both external (the actual work done) and internal (the actual physiological and psychological stress elicited by the given work) training load experienced by an athlete by multiplying exercise duration (in minutes) or volume and RPE (i.e. Borg CR10 scale), typically reported by an athlete 30 min after a training session. Despite the simplistic nature of this method, sRPE has been shown to be a valid and reliable tool to monitor training load. The validity of sRPE has been assessed against other, more objective measures of internal training load such as [Bla] (Coutts et al., 2009), HR (Rodríguez-Marroyo et al., 2012) and ventilatory thresholds (Seiler and Kjerland, 2006). In addition, sRPE has the capacity to measure training load independent of the mode and type of exercise (aerobic, skill, strength based) that are regularly performed in training programmes of athletes including swimmers (Foster et al., 2001; Wallace et al., 2008). Whilst sRPE represents a valuable monitoring tool for practitioners, the sensitivity of this method can be questioned. Specifically, although the Borg CR10 scale includes power functions to account for the non-linear ‘dose-response’ relationship of exercise (Borg and Kaijser, 2006), the ability of athletes, particularly youth athletes, to self-assess their perception of load and effort may be unreliable (Bourdon et al., 2017; Wallace et al., 2008), and so requires education to overcome those issues. Equally, similar sRPE scores could be assigned to sessions that have very different physiological effects (e.g., 60 min easy swim at RPE 2 and 15 min very hard swim at RPE 8 both produce sRPE load of 120 AU). Despite these shortfalls, sRPE represents a valid tool which can be utilised in applied swimming practice to monitor training load (Wallace et al., 2008).

Chapter 2: Literature review

2.8.2 Heart rate variability

Apart from sRPE, another measure that has received considerable attention from the scientific and applied community in recent years is heart rate variability (HRV) (Bellenger et al., 2016). HRV represents the beat-to-beat (R-R interval) variation of ventricular contraction within the QRS complex across consecutive cardiac cycles. This consequently provides an estimate of the interplay of an individual's sympathetic (fight or flight/ training stress) and parasympathetic (rest and digest/ training recovery) autonomic nervous system activity (ANS), and thus provides an indirect measure of the athlete's stress-recovery status (Bellenger et al., 2016; Plews et al., 2013a). HRV has been historically collected through ECG recordings, although the invention of HR chest straps or more recently photoplethysmography (PPG) has enabled practitioners to collect valid HRV measures more easily and in non-clinical applied environments (Plews et al., 2017). Traditionally, the parasympathetic arm of HRV measured as the the root-mean-square difference of successive normal *R–R* intervals (rMSSD) via time domain analysis, or high frequency (HF) power via power spectral domain analysis, have been investigated, and the changes in these parameters have been associated with changes in performance (Plews et al., 2013b; Chalencon et al., 2012; 2015), training load and recovery (Chalencon et al., 2012; 2015), health (Williams et al., 2017; Hellard et al., 2011), serum creatine kinase (Weippert et al., 2018) as well as changes in subjective well-being measures (Flatt, Esco and Nakamura, 2018). This has consequently made HRV a popular objective tool to monitor well-being and training adaptations in athletes. Indeed, considering that athletes and coaches always strive to find an optimal balance between training and recovery and often hover around the 'tipping point' between functional (positive adaptations) and non-functional (negative adaptations) overreaching to maximise the benefits of training, using HRV as a monitoring tool has shown the potential to assist coaches with decisions as to when 'enough is enough' or when it might be possible to increase training loads further for extra positive adaptations (Plews et al., 2013a).

Indeed, so called 'HRV guided training' approaches, where athletes are only allowed to proceed with high-intensity sessions when their HRV values are within acceptable levels have recently gained popularity, and have been shown to elicit more stable HRV and superior adaptations when compared to non-guided, predefined training programmes (Javaloyes et al., 2019; Vesterinen et al., 2016b; Kiviniemi et al., 2007).

Chapter 2: Literature review

For example, the recent study of Javaloyes et al. (2019) examined the effect of an 8-week HRV-guided and predefined training prescription in well-trained cyclists and found that cyclists who engaged in a HRV-guided programme significantly improved peak power output (5%), power corresponding with the second ventilatory threshold (14%), and performance in a 40-min simulated TT (7%), whilst cyclists who followed a predefined programme did not achieve significant improvement in any of the measured parameters, despite spending a greater proportion of their training time between the first and second thresholds. Similarly, Vesterinen et al. (2016b) observed significant improvements in 3000 m running performance in a group of well-trained runners who followed an 8-week HRV-guided programme, whilst runners who followed a predefined programme did not achieve significant improvements in this test despite completing a greater number of moderate- and high-intensity sessions. Both authors of the aforementioned studies attributed these results to better timing of the high-intensity training sessions i.e., HIIT is only prescribed when the athlete is in optimal conditions to perform it. This suggests that HRV-guided training has the potential to optimise the dose-response relationship and minimise the chances of prescribing an unnecessary training stimulus to athletes, therefore reducing the risk of over-training or overuse injury.

Indeed, utilising the Banister Impulse-Response (I-R) model, which has been used to mathematically describe dose-response relationship for decades (Banister et al., 1975), Chalencon et al. (2012; 2015) demonstrated that HRV can be used as a suitable substitute for performance measures in mathematical modelling of training effects in competitive swimmers. Specifically, the I-R model has been typically used to mathematically describe the relationship between training dose (i.e., load) and training response (i.e., performance). The model works on the assumptions that training dose elicits both a positive (fitness) and negative (fatigue) training effect on performance by utilising four model parameters, which describe gain and decay for both fitness and fatigue. The model assumes that fatigue has a faster effect on performance than fitness, resulting in initially reduced performance, however as fatigue dissipates faster than fitness, this consequently results in improved performance (Clarke and Skiba, 2013). Chalencon et al., (2012) however argued, that although this model could provide useful information in order to optimise the dose-response relationship for individual athletes, the requirement for substantial amount of performance data (at least one

Chapter 2: Literature review

performance test a week is required) limits its use in applied practice, in which coaches are reluctant to change training plans. Although Chalencon et al. (2012, 2015) demonstrated that there was a high degree of accuracy between actual and predicted performance (r : 0.92 and 0.87) and actual and predicted HRV (r : 0.89 and 0.87), as well as very large correlations between HRV and performance behaviour, the methodology utilised for the model's input (training load) and output (400 m TT and HRV) could be improved to increase the accuracy and transferability of this method to applied practice. From the perspective of accuracy, Chalencon et al. (2012; 2015) calculated training load as the sum of kilometres swam at each exercise intensity, multiplied by their HR delta ratio and respective coefficients associated with seven exercise intensities that were demarcated based on 400 m (estimate of $\dot{V}O_{2\text{MAX}}$) and 1500 m (estimate of OBLA) maximal performance tests only. Additionally, these studies attempted to calculate water equivalents of dry land training by assuming that a one-hour land session composed of 30 minutes of low intensity warm up and stretching exercises, 15 minutes of submaximal strength exercises and 15 minutes of maximal strength exercises is equivalent to two kilometres of swimming. As no direct measures of boundaries demarcating exercise intensity domains were obtained, and dry land structure can vary from session-to-session, the accuracy of the input into the model could be arguably improved. Additionally, Chalencon et al. (2012; 2015) used only one weekly measure of nocturnal HRV and utilised the HF component of HRV as opposed to the weekly averages of log-transformed square root of the mean sum of the squared differences between R-R intervals (Ln rMSSD), which has been shown to be more reliable and more practically applicable for daily monitoring of HRV compared to other HRV indices (Plews et al., 2013a,b; Al Haddad et al., 2011). From the perspective of feasibility, coaches and practitioners might not be able to calculate training load on a regular basis utilising the method described above due to limited time, and might not have the resources to buy multiple heart rate monitors capable of measuring nocturnal HRV indices and time to set up these tools to measure HRV on a daily basis. Therefore, in order for practitioners to benefit from the promising findings of Chalencon et al. (2012; 2015), further studies are required to investigate whether the same or a higher level of accuracy can be achieved with more simplistic and affordable methods, without compromising on validity.

Chapter 2: Literature review

Indeed, the recent emergence of smartphone applications (e.g., HRV4Training) and technologies (e.g., PPG) has substantially improved practitioners' accessibility and ability to record HRV accurately and on a day-to-day basis using a mobile phone only (Plews et al., 2017). Plews et al. (2017) assessed the validity of smartphone PPG (HRV4Training) and heart rate sensor in the measurement of HRV and found that both of the methods provided an acceptable level of agreement with HRV derived from ECG, suggesting that smartphone PPG technology is a suitable (and more practical) method of collecting HRV in applied practice. A further advantage of applications such as 'HRV4Training' is in the in-built capacity to record daily training load (e.g. sRPE) as well as subjective well-being measures, that were recently emphasised as important to account for to ensure appropriate interpretation of HRV behaviour (Flatt, Esco and Nakamura, 2018). Additionally, the low-cost, easy data access, and the ability of athletes to collect the data themselves, make such applications a suitable tool to investigate whether the promising findings from Chalencon's et al. (2012; 2015) can be replicated. Doing so would enable practitioners to better monitor, plan and prescribe training and recovery more specifically to an individual athlete's needs.

2.9 Rationale for the current work

This review of the literature has highlighted that in swimming practice there is a need for physiological testing that could allow valid assessment of swimmers' physiological profiles (both aerobic and anaerobic) across multiple strokes on a regular basis. Importantly, such testing needs to be accessible to the wider swimming community (i.e., those with limited resources, time, and physiological expertise). The critical speed concept framework assessed via 3MT has shown promising application in multiple sports, however, its validity and reliability has not been effectively explored in competitive swimmers. Consequently, the validity and reliability assessments of 3MT are required before application of this concept and test to swimming training can be explored and compared to currently utilised procedures. Additionally, despite the promising applications of the CS concept for personalised HIIT prescription, this approach has not been examined extensively in swimming and so it is currently unknown what effects this novel type of training might have on physiological, technical and performance parameters. Indeed, it is also unknown whether this approach could be used effectively when applied to a training programme of highly-trained swimmers with reduced volume of training as a 'lower-volume,

Chapter 2: Literature review

higher-intensity' training alternative. Finally, given that HRV has become a promising monitoring tool which could be also utilised as an alternative measure for performance monitoring via the Banister Impulse-Response model, and given that collection of HRV and measures of training and non-training related stressors in a short space of time has recently become feasible, it would be useful to examine if the initial findings supporting these approaches could be replicated with methods easily accessible to swimming coaches and swimmers alike.

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

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3.1 Abstract

Purpose: Firstly, to assess the concurrent and predictive validity of the 3-min all-out test (3MT) against the conventional methods (CM) of determining critical speed (CS) and the finite capacity to work above CS (D'), and secondly, to examine the test-retest reliability of the 3MT in highly-trained swimmers. **Methods:** Thirteen national and international swimmers (age: 16 ± 1 y, body mass: 64.7 ± 8.8 kg, stature: 1.76 ± 0.07 m) completed 200 m, 400 m, 600 m and 800 m time trials (TT), and two 3MT over a 2-week period. The distance-time (DT) and speed-1/time ($1/T$) models were used to determine CS and D' from the four TT and were compared to CS and D' derived from the 3MT. **Results:** CS_{3MT} (1.33 ± 0.06 m.s⁻¹) was not different from CS_{CM} (1.33 ± 0.06 m.s⁻¹, $p=0.19$) and correlated nearly perfectly with CS_{CM} ($r=0.95$, $p<0.0001$). D'_{3MT} (19.50 ± 3.52 m) was lower compared to D'_{DT} (23.30 ± 6.24 m, $p=0.024$) and $D'_{1/T}$ (22.15 ± 5.75 m, $p=0.09$). Correlations between D'_{3MT} and D'_{CM} were very large ($r=0.79$, $p=0.002$). There were no significant differences and nearly perfect correlations ($r>0.90$, $p<0.0001$) between actual TT times and TT times predicted from 3MT parameters. CS and D' between the two 3MT trials were not different ($CS_{3MT1}=1.34 \pm 0.06$ m.s⁻¹, $CS_{3MT2}=1.34 \pm 0.06$ m.s⁻¹; $D'_{3MT1}=18.36 \pm 4.07$ m, $D'_{3MT2}=17.54 \pm 3.11$ m; $p>0.05$). Correlations between two 3MT trials were nearly perfect and very large for CS ($r=0.97$) and D' ($r=0.87$) ($p<0.05$), respectively, with coefficients of variation of 0.9% for CS and 9.1% for D' . **Conclusion:** 3MT is a valid protocol for the estimation of CS and produces high test-retest reliability for CS and D' in highly-trained swimmers.

Key words: critical speed, 3-minute all-out, testing, monitoring, swimming

3.2 Introduction

It is well established that when swimming, rowing, running or cycling at a relatively fast but comfortable pace, the work rate can be sustained for a considerable period of time without immediate fatigue (Jones et al., 2010). However, once the work rate

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

increases even slightly beyond this ‘comfortable pace’, substantial increases in perceived effort and a highly predictable reduction in exercise tolerance are observed. Indeed, this phenomenon can be captured in the speed-duration relationship that has provided a strong physiological and mathematical basis for the critical speed (CS) concept established by Monod and Scherrer in 1965 (Jones and Vanhatalo, 2017; Poole et al., 2016). The CS concept describes the limits of severe intensity exercise by the demarcation of two physiological parameters; critical speed (CS) and the finite work capacity above critical speed (D'), often referred to as ‘fatigue threshold’ and ‘fatigability constant’, respectively (Poole et al., 2016). Whilst CS represents the highest speed that can be maintained for an extended period of time via mostly aerobic energy supply, the capacity to exercise above CS is finite (D'). Indeed, exercise in the severe exercise intensity domain is accompanied with the development of an oxygen uptake ($\dot{V}O_2$) slow component, a reduction in D' , metabolic perturbations, and loss of muscle contractile efficiency, which eventually drives $\dot{V}O_2$ to its maximum, if sufficient time is provided (Jones et al., 2010). Considering that CS represents a boundary between steady and non-steady state exercise intensities and D' represents the capacity to work above the CS, the CS concept is often considered as a more meaningful parameter for optimising fatigue, training and performance processes than lactate threshold or $\dot{V}O_{2MAX}$ (Vanhatalo, Jones and Burnley, 2011; Jones et al., 2010).

Originally, testing protocols used for the determination of CS and D' required 3-5 time-to-exhaustion (TTE) trials or time trials (TT) to be completed on separate days (Mondon and Scherrer, 1965; Moritani et al., 1981). Using the conventional method, CS and D' can be derived from the hyperbolic speed-time relationship (Whipp et al., 1982), linear distance-time (DT) or speed-1/time ($1/T$) relationships (Mondon and Scherrer, 1965). Although the CS concept has been studied for decades in one form or another, some of the key features and advancements of this concept have come to light relatively recently. In 2006, a 3-min all-out test (3MT) was developed by Burnley, Doust and Vanhatalo (2006), that has allowed the calculation of critical power (CP) (equivalent to CS) and W' (equivalent to D') in a single cycling exercise bout. According to these authors the all-out effort in the first 150 s is sufficient to deplete a subject’s W'/D' , resulting in an average power/speed for the last 30 s that corresponds to the CP/CS. Indeed, this test could now replace the cumbersome nature of the conventional protocol, which could be challenging to complete for athletes with

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

demanding training schedules, and has potentially prevented the wider application of the CS concept despite its broad applicability (Jones et al., 2010). Since the 3MT has been developed, the CS concept has found its extensive application in prediction of performances, prescription of individualised training, assessment and monitoring of physical fitness as well as in developing optimal warm-up, racing and pacing strategies (Jones and Vanhatalo, 2017; Pettitt, 2016). Although, the 3MT was validated and has found its use in multiple modes and contexts of exercise such as cycling (Pettitt et al., 2015; Black et al., 2014; Vanhatalo, Doust, Burnley, 2007), running (De Aguiar et al., 2018; Broxterman et al., 2013; Pettitt, Jamnick and Clark, 2012), rowing (Cheng et al., 2012), soccer (Clark et al., 2013), rugby (Kramer et al., 2019), military special forces (Hoffman et al., 2016), shuttle running (Saari et al., 2019), arm crank (Flueck et al., 2015), and knee extension exercise (Burnley, 2009), only two attempts have been made to validate the 3MT in free swimming (Tsai and Thomas, 2017; Mitchell et al., 2018a). Tsai and Thomas (2017) examined the validity of the 3MT in recreational swimmers and triathletes and found that D'_{3MT} was lower compared to conventional methods, whilst CS_{3MT} was not different compared to the CS_{DT} model but was lower compared to $CS_{1/T}$. Mitchell et al. (2018a) assessed the validity of a modified 3MT (12 x 25 m) in national and international swimmers, and found that CS derived from the modified 3MT was significantly higher compared to the CS derived from two TT. Whilst there was no significant difference between D' values derived from the modified 3MT and TT, the result for D' did not display a sufficient level of agreement. However, both of these studies were subject to a number of potential limitations: Tsai and Thomas (2017) used a recreational and heterogeneous sample of athletes; combined primary (TT using a push-off start) and secondary data (race results using a dive start) for derivation of CS and D' in the conventional methods; used an inconsistent and high-intensity warm-up; and omitted to implement a familiarisation with 3MT. Mitchell et al. (2018a), used only two TT (100 and 200 m) that were obtained from races (using a dive start and turns), both with a duration $< \sim 2.5$ min; excluded turns from the 3MT; and allowed ~ 5 s rest between each 25 m. The aforementioned factors may have impacted on the results, given the previous research demonstrating the impact of these variables on CS and D' (Jones et al., 2010; Ferguson et al., 2010; Triska et al., 2017; Dekerle et al., 2002). Accordingly, to date, no study has assessed the validity and reliability of the traditional 3MT in highly-trained swimmers. Considering that physiological testing can be especially challenging in

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

swimming due to environmental and technological constraints, the 3MT represents a promising tool that has the potential to allow complex assessments of large groups of swimmers with minimal resources, time and expertise.

Therefore, the aim of the present study was to assess the concurrent and predictive validity and apply a field-based 3MT in a squad of national and international swimmers by comparing the parameters of the speed-time relationship derived from a 3MT with those derived from a series of four TT used for the conventional method of CS and D' determination. We hypothesised that 1) the end-speed in a 3MT (CS_{3MT}) will be equivalent to CS derived from the conventional models (CS_{CM}), and 2) the D' derived from the same test (D'_{3MT}) will be equivalent to D' derived via the conventional models (D'_{CM}). The second aim of the current study was to assess test-retest reliability of the 3MT in this setting.

3.3 Methods

3.3.1 Participants

A performance squad of 13 healthy swimmers (6 M, 7 F, age: 16 ± 1 y, body mass: 64.7 ± 8.8 kg, height: 176 ± 7 cm) volunteered to participate in this study, which received approval from the Research Ethics Approval Committee for Health at the University of Bath. All participants were swimmers that regularly competed in one or more national or international events per year and had personal best times for their primary event of $\sim 85\%$ in relation to the world record. The swimmers completed a training volume of ~ 45 km.week⁻¹, 8-9 swim sessions, 2-3 land sessions.week⁻¹ and had training histories of 7.5 ± 2.9 y. The participants had no known history of any diseases and were not taking any medications that might have affected the variables under investigation. Prior to any testing all subjects and parents were informed of the protocol, risks and discomfort associated with the procedure and potential benefits, and gave their written consent. One swimmer was excluded from the validation analyses and two swimmers were excluded from the reliability analyses, due to either not following the instructions of the procedures or health issues.

3.3.2 Experimental design

The protocol consisted of seven visits to the swimming pool. First, the subjects performed a 3MT familiarization trial, which was not included in the subsequent data

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

analysis. On the following visits and on separate days, subjects performed four TT and two 3MT to determine CS and D'. Each trial was preceded by 5 min warm-up at low intensity to minimise an impact of prior exercise on D' (Jones et al., 2010; Vanhatalo and Jones, 2009) and was followed by 5 min rest. The front crawl (freestyle) technique was adopted in all TT and 3MT. All trials were completed in a 50 m pool with a push off start, flip turns, and occurred at the same time of the day (± 1 h) in order to minimise an impact of circadian variation on performance (Drust et al., 2005). All swimmers were encouraged to come to the testing rested, fully hydrated and having eaten sufficiently, as if they would be going into a competitive event. Training volume was adjusted appropriately to maximise results of the study.

3.3.3 Conventional protocol

The conventional protocol requires a subject to complete 3-5 TTE or TT trials lasting 2-15 min on separate days (Hill, 1993; Vanhatalo, Doust, Burnley, 2007). CS and D' were estimated from four TT in this study. Each individual was asked to complete a 200 m, 400 m, 600 m and 800 m freestyle TT in the fastest possible time on separate days. Stroke rate (SR) for each TT was also determined from the middle section of the pool (20-30 m) to minimise effect of turns, using the following formula:

Equation 3.1

$$SR = (60/\text{the time it takes to do three full stroke cycles}) \times 3$$

3.3.4 Three-min all-out test

Subjects were instructed to swim at an 'all out' swimming speed i.e. "as fast as you possibly can at any given time during the test". This is important to emphasise as pacing could confound results in this test (Jones et al., 2010). Swimming splits were recorded using a stopwatch (Finis Inc., 3 x 100m, California, USA) at every 10 m as the swimmer was visualised passing the cone. Ten meters stages were marked with fluorescent cones placed parallel to the swimmer's lane at every 5 m along the pool deck to enable calculating split times as well as displacement (D) of the swimmer at 150 and 180 s. As a swimmer was approaching 150 s and 180 s, a 10 s countdown was given to the researcher that walked with a cone alongside the swimmer and a cone was placed at 150 s and 180 s at the furthest point reached (i.e., a hand). Subjects were also filmed from an elevated area at the opposite side of the pool using a camera

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

mounted on a tripod that was used to double check the displacement and velocity at each cone as well as to analyse SR. Distance at 150 s (D_{150}) and 180 s (D_{180}) were recorded using a 50 m tape measure placed parallel to the swimming lane and were used for the calculation of CS and D' using the following formulas (Courtright et al., 2016; Pettitt, Jamnick and Clark, 2012):

Equation 3.2

$$CS = (D_{180} - D_{150})/30$$

Equation 3.3

$$D' = [(D_{150}/150) - CS] \times 150$$

Strong verbal encouragement was provided throughout the tests, and time to complete each trial was recorded to the nearest hundredth of a second or cm in the case of displacement. Subjects were not informed of the elapsed time or their performance to prevent pacing. The first 3MT trial was used for the validation analysis, mean 3MT speed-time and SR-time profiles.

3.3.5 Statistical analyses

Linear regression was used to calculate CS and D' from the distance-time model (DT) and the speed-1/time model (1/T) that were obtained from the four TTs. A one-way repeated measures ANOVA was used to test for differences in CS and D' between 3MT and the conventional models. A Bonferroni correction was applied for post-hoc comparisons in the presence of a significant F value. Mean 3MT speed-time and SR-time profiles were calculated at 15 s intervals assuming a linear regression within the closest distance intervals that cross each of the 15 s interval, excluding turns. A Pearson correlation coefficient and a Bland-Altman analysis were used to assess the relationships and the limits of agreement (LOA) between CS and D' estimated from the conventional methods and 3MT, respectively. Default thresholds for correlations were 0.1, small; 0.3, moderate; 0.5, large; 0.7, very large; 0.9, nearly perfect (Hopkins, 2002a). The acceptable limits of agreement of differences was defined as 5% of mean CS (Tsai and Thomas, 2017) and as 10% of mean D' . Predicted times for TT were calculated using the following equation (Pettitt, 2016):

Equation 3.4

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

$$TT \text{ time} = (\text{distance} - D'_{3MT}) / CS_{3MT}$$

Paired-sample t-test and bivariate correlation were used to assess differences and relationships between actual and predicted TT times, respectively. The intra-class correlation coefficient (ICC), raw and standardised typical error (TE) of measurement and coefficient of variation (CV) were used to assess test-retest reliability of the 3MT. Default magnitude thresholds for the standardised TE of measurement were 0.2, 0.6, 1.2, 2.0, 4.0 for small, moderate, large, very large and extremely large, respectively (Hopkins, 2010; Hopkins et al., 2009). Paired-sample t-test and 95% confidence intervals (CI) of the mean differences were used to compare the responses between the two 3MT tests. The SPSS software package (v 24, SPSS, Chicago, IL) was used for statistical analysis. Statistical significance was accepted at $p < 0.05$ level, with data presented as means \pm SD. Where DT and 1/T models provided identical results compared to 3MT, 'CM' abbreviation was used for succinctness.

3.4 Results

3.4.1 Validity

The mean 3MT profile is shown in **Figure 3.1**. When speed data were reduced to 15 s averages and compared, significant differences were observed between time bins ($F_{(2.82, 31.03)} = 83.76, p < 0.0001$). Comparing one time interval to the previous, there was a significant decrease in speed in the first 60 s, before the speed stabilised in the last 120 s. **Figure 3.2** demonstrates the derivation of the CS and D' parameters using the DT, 1/T models and the 3MT in a representative subject. **Table 3.1** provides a summary of CS and D' estimated from the DT, 1/T models and 3MT along with standard errors (SE) associated with the parameters modelled from the CM. There was no significant difference between CS_{3MT} , CS_{DT} or $CS_{1/T}$ ($F_{(1.19, 13.07)} = 1.89, p = 0.19$). CS_{3MT} correlated nearly perfectly with CS_{CM} ($r = 0.95, p < 0.0001$). There was a significant difference between the three estimates of D' ($F_{(1.48, 16.34)} = 7.77, p = 0.007$). D'_{DT} was significantly higher ($p = 0.024$) compared to D'_{3MT} and there was a trend for significantly higher $D'_{1/T}$ ($p = 0.09$) when compared to D'_{3MT} . There was a very large positive correlation between D'_{3MT} and D'_{CM} ($r = 0.79, p = 0.002$). There were no significant differences in the estimated parameters between the DT and 1/T models ($p > 0.05$) and the parameters estimated also correlated nearly perfectly between the two conventional models (CS: $r = 0.99$; D': $r = 0.93$; $p < 0.0001$).

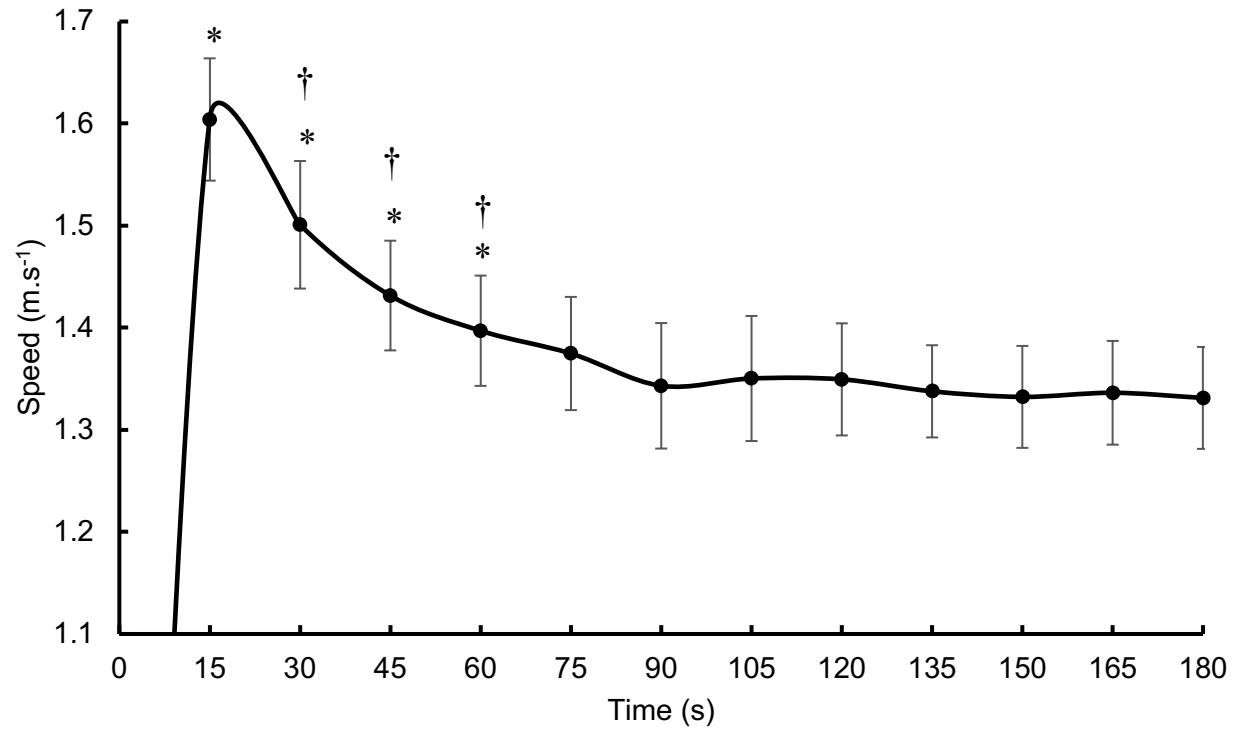


Figure 3.1. The group mean speed-time profile of the 3-min all-out test. * $p < 0.05$ compared to the speed in the last 30 s, † $p < 0.05$ compared to the previous 15 s speed interval, $n=12$.

**Chapter 3: Validity and reliability of the 3-min all-out test
in national and international competitive swimmers**

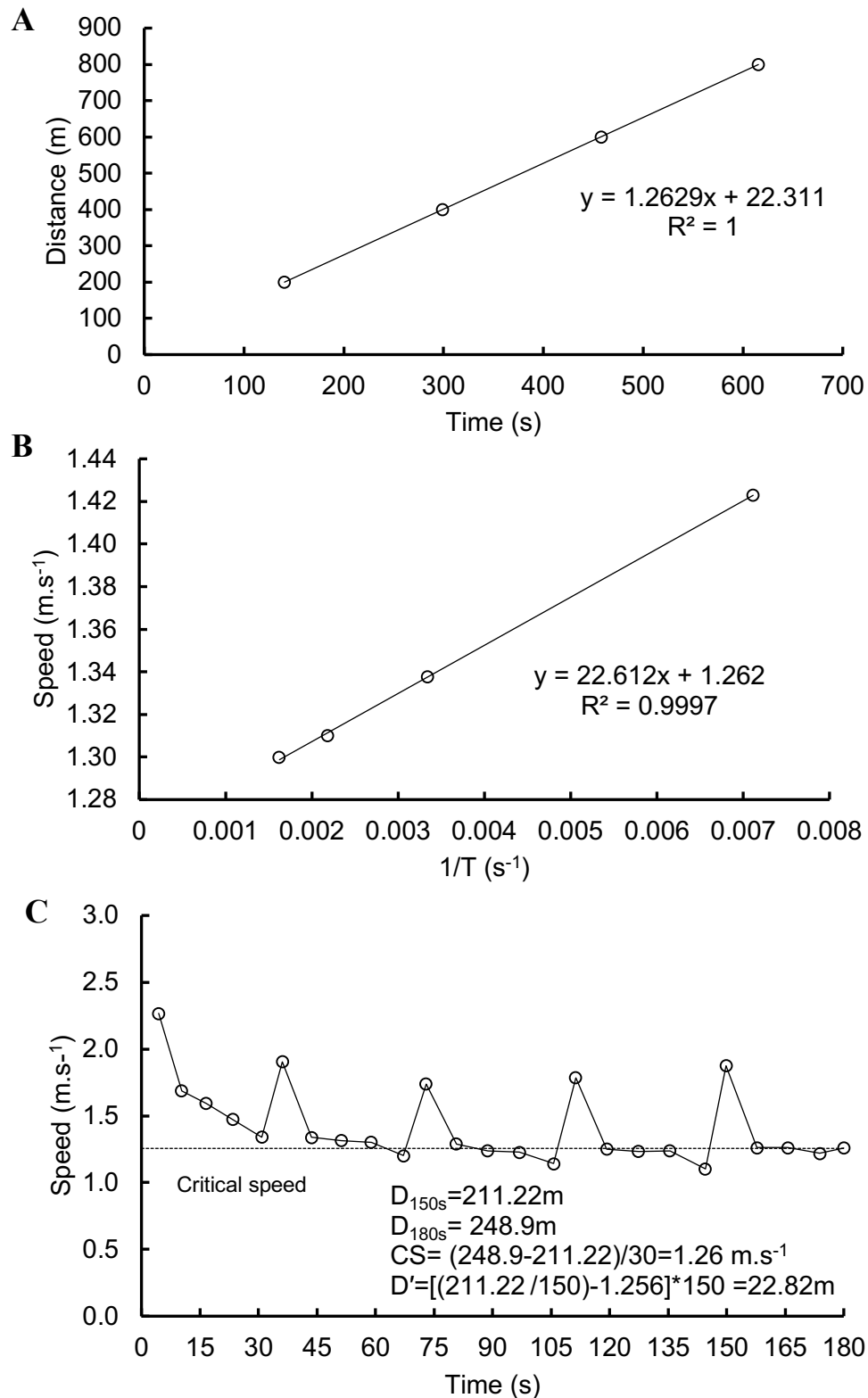


Figure 3.2. The derivation of the critical speed (CS) and D' estimates from the linear distance-time (A), speed-1/time (B) models and a 3-min all-out test (C) in a representative subject.

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

Table 3.1. Comparison of the critical speed and D' derived from the 3-min all-out test and conventional models.

Subject	CS estimates (m.s ⁻¹)					D' estimates (m)					R ²	
	3MT	D-T	SE	1/T	SE	3MT	D-T	SE	1/T	SE	D-T	1/T
1	1.33	1.29	0.02	1.30	0.02	21.60	27.55	9.35	26.42	4.73	1.00	0.94
2	1.25	1.25	0.002	1.25	0.002	22.40	23.41	0.94	23.49	0.47	1.00	1.00
3	1.26	1.26	0.002	1.26	0.001	22.82	22.31	0.72	22.61	0.29	1.00	1.00
4	1.29	1.26	0.004	1.26	0.003	23.30	32.44	1.53	32.25	0.77	1.00	1.00
5	1.29	1.29	0.005	1.29	0.003	15.70	16.03	1.94	16.64	0.80	1.00	1.00
6	1.42	1.42	0.01	1.43	0.01	18.35	20.81	5.03	17.30	2.32	1.00	0.97
7	1.37	1.35	0.01	1.35	0.01	16.20	22.49	4.70	23.58	1.94	1.00	0.99
8	1.36	1.32	0.01	1.33	0.01	21.51	27.64	4.38	25.85	2.66	1.00	0.98
9	1.36	1.39	0.01	1.39	0.01	14.10	17.36	3.87	17.98	1.69	1.00	0.98
10	1.30	1.30	0.01	1.30	0.005	21.50	21.80	2.79	21.39	1.24	1.00	0.99
11	1.39	1.38	0.02	1.40	0.02	22.20	34.08	7.55	27.40	4.22	1.00	0.96
12	1.39	1.39	0.01	1.40	0.01	14.30	13.67	3.10	10.88	2.05	1.00	0.93
Mean	1.33	1.33	0.01	1.33	0.01	19.50	23.30*	3.83	22.15	1.93	1.00	0.98
SD	0.06	0.06	0.01	0.06	0.01	3.52	6.24	2.62	5.75	1.41	0.00	0.02

CS, critical speed; D', finite work capacity above CS; 3MT, the 3-min all-out test; D-T, the distance-time model; 1/T, the speed-1/time model; SE, standard error; n=12; * $p < 0.05$ compared to the 3MT

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

Figures **Figure 3.3** and **Figure 3.4** demonstrate the relationships and bias \pm 95% LOA between estimates derived from 3MT and conventional models. Mean bias between CS_{3MT} and CS_{DT} was 0.01 ± 0.02 m.s⁻¹ (95% CI: -0.003 to 0.02 m.s⁻¹) and between CS_{3MT} and CS_{1/T} was 0.01 ± 0.02 m.s⁻¹ (95% CI: -0.01 to 0.02 m.s⁻¹). Bland-Altman plots of CS between 3MT and conventional models evidenced that the 95% LOA ranged from -0.03 to 0.05 m.s⁻¹ (DT: -0.03 to 0.05 m.s⁻¹, 1/T: -0.03 to 0.04 m.s⁻¹), which is within the value of 5% CS defined *a priori* as acceptable. The mean bias between D'_{3MT} and D'_{DT} was -3.8 ± 4.07 m (95% CI: -6.39 to -1.21 m) and between D'_{3MT} and D'_{1/T} was -2.65 ± 3.68 m (95% CI: -4.99 to -0.31 m), showing consistently lower D'_{3MT} value when compared to D'_{DT} and D'_{1/T}. Bland-Altman plots of D' between 3MT and conventional models with the 95% LOA ranged from -11.78 to 4.56 m (D-T: -11.78 to 4.18 m, 1/T: -9.86 to 4.56 m), which is not within the value of 10% D' defined *a priori* as acceptable. The standard error of the estimate (SEE) between CS_{3MT} and CS_{CM} was 0.02 m.s⁻¹ (95% CI: 0.01 to 0.04 m.s⁻¹; ~1.5% of the mean CS_{3MT}). The SEE between D'_{3MT} and D'_{DT} was 4.01 m (95% CI: 2.80 to 7.03 m; ~20.6% of the mean D'_{3MT}) and 3.71 m (95% CI: 2.60 to 6.52 m; ~19% of the mean D'_{3MT}) between D'_{3MT} and D'_{1/T}. When the calculation of predictive TT times was modelled with CS_{3MT} and D'_{3MT}, the calculation yielded times consistent with those actually performed and nearly perfect correlations were observed (see **Table 3.2**).

Table 3.2. Comparison of the actual versus predicted time trial times.

	200 m (s)	400 m (s)	600 m (s)	800 m (s)
Actual TT	134.18 \pm 5.54	283.44 \pm 12.97	436.65 \pm 19.40	587.02 \pm 24.29
Predicted TT	135.41 \pm 4.95	285.50 \pm 10.95	435.59 \pm 17.17	585.69 \pm 23.46
<i>r</i>	0.93*	0.98*	0.94*	0.96*

TT, time trials; * $p < 0.0001$

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

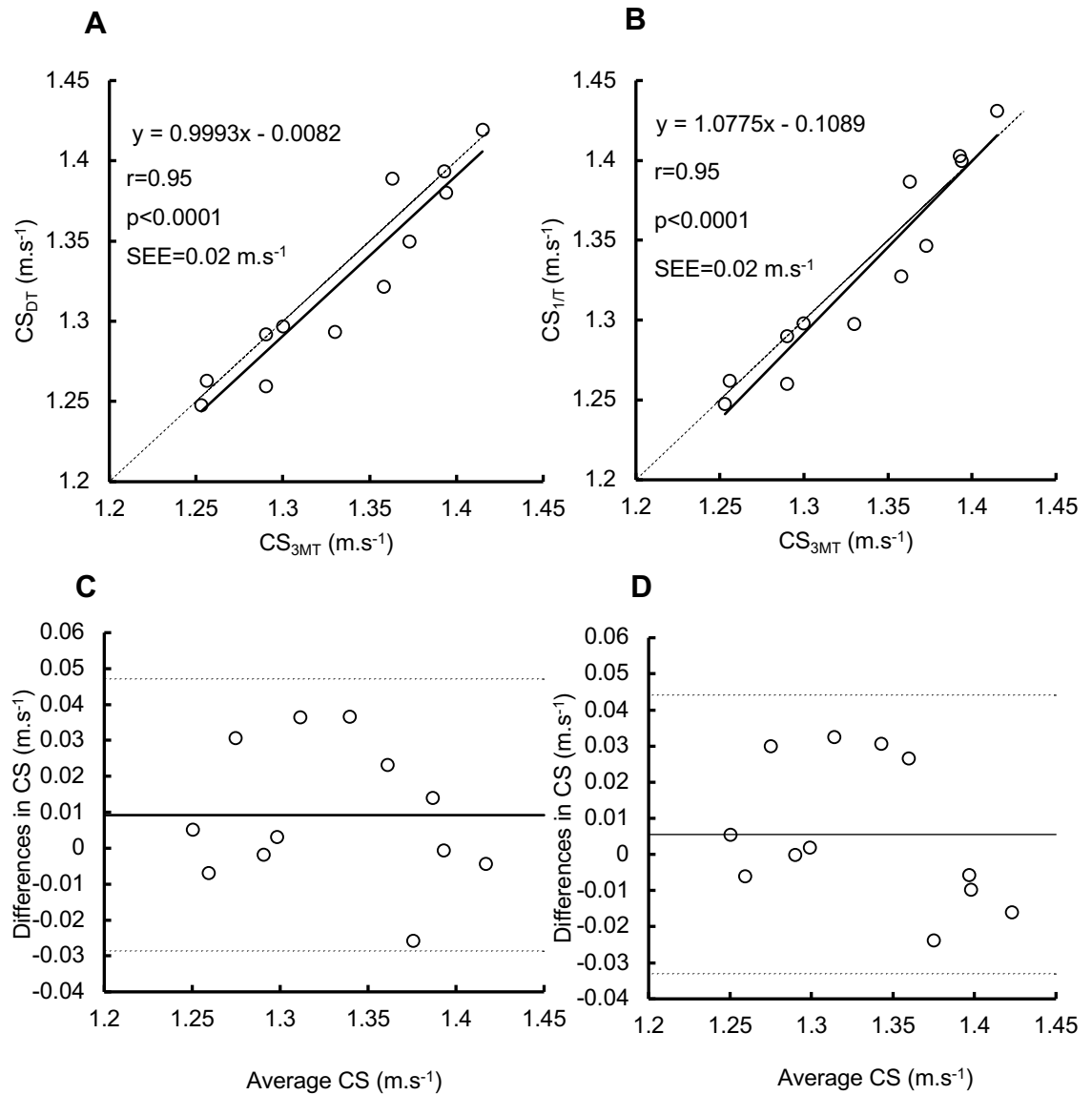


Figure 3.3. Correlation and Bland-Altman analyses for differences in CS between the 3MT and the distance-time model (A, C) and between the 3MT and the speed-1/time model (B, D). In the panels A and B, the solid line is the line of best-fit linear regression and the dashed line is the line of identity. In the panels C and D, the solid horizontal lines represent the mean difference between the CS_{3MT} and CS_{DT} and CS_{3MT} and $CS_{1/T}$, respectively, and the dashed lines represent the 95% limits of agreement; $n=12$.

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

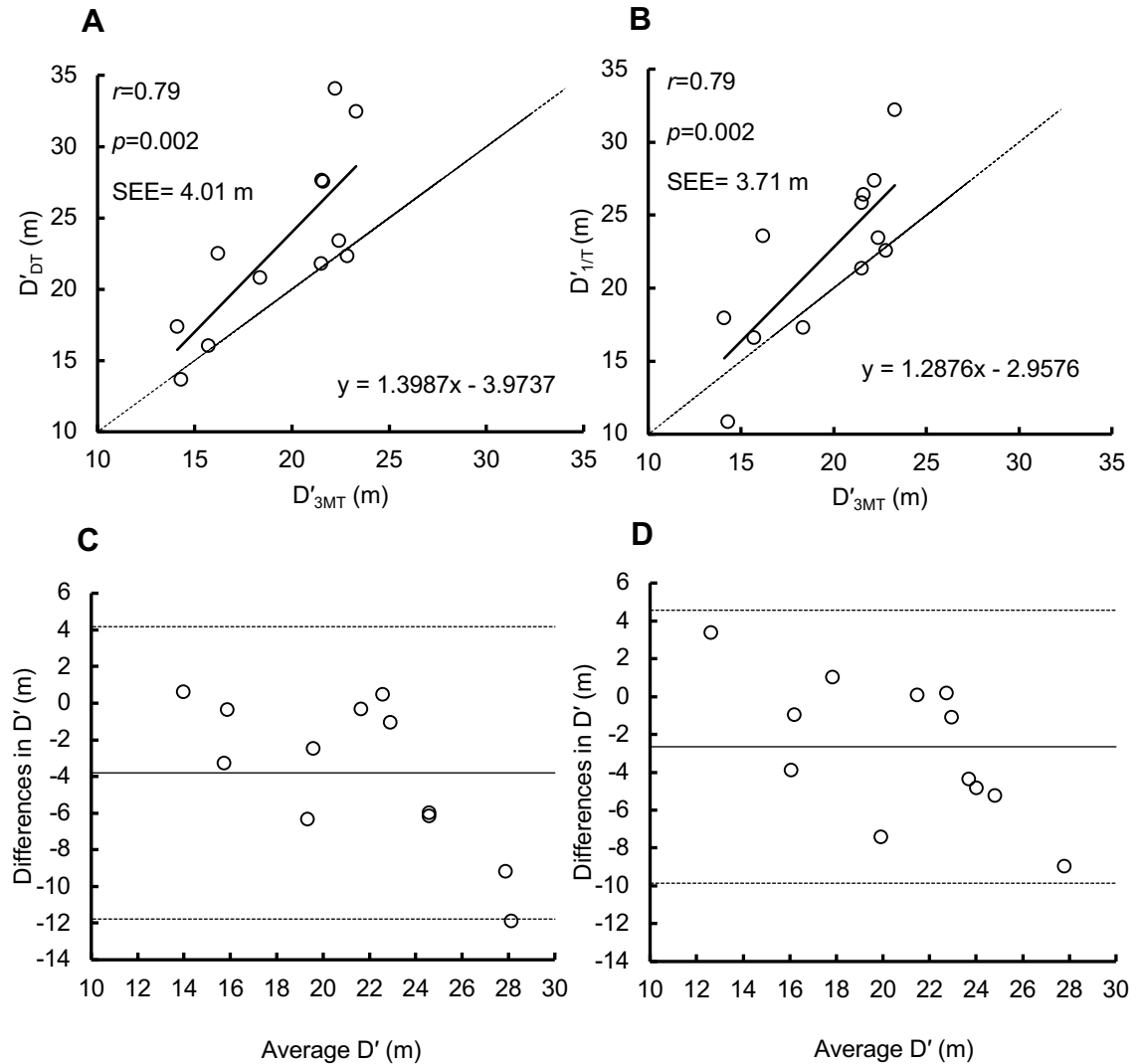


Figure 3.4. Correlation and Bland-Altman analyses for differences in D' between the 3MT and the distance-time model (A, C) and between the 3MT and the speed-1/time model (B, D). In the panels A and B, the solid line is the line of best-fit linear regression and the dashed line is the line of identity. In the panels C and D, the solid horizontal lines represent the mean difference between the D'_{3MT} and D'_{DT} and D'_{3MT} and $D'_{1/T}$, respectively, and the dashed lines represent the 95% limits of agreement; $n=12$.

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

There were significant differences in SR between 3MT and TT ($F_{(2.37, 26.10)}=53.87$, $p<0.0001$). The SR was significantly higher in 3MT (40.62 ± 3.37 cycles.min⁻¹) compared to SR in 400 m (37.70 ± 4.05 cycles.min⁻¹, $p=0.005$), 600 m (36.78 ± 4.01 cycles.min⁻¹, $p<0.0001$) and 800 m TT (36.59 ± 4.20 cycles.min⁻¹, $p<0.0001$). There was no significant difference between SR in 3MT and in 200 m TT (42.43 ± 4.58 cycles.min⁻¹, $p=0.312$). There was a negative correlation between SR in 3MT and D'_{3MT} ($r=-0.56$, $p=0.056$), D'_{DT} ($r=-0.26$, $p>0.05$) and $D'_{1/T}$ ($r=-0.21$, $p>0.05$). During the 3MT, the SR in the first 30 s was significantly higher compared to the SR in the last 30 s and a decline in SR coincided with the decline in speed (see **Figure 3.5**).

3.4.2 Test-retest reliability

Test-retest reliability for CS and D' were high between the two 3MT trials conducted on separate days (see **Table 3.3**). **Table 3.3** also shows that other performance parameters had high reliability (ICC=0.91-0.98, $p<0.05$). There were no significant differences in CS between two 3MT trials ($CS_{3MT1}=1.34 \pm 0.06$ m.s⁻¹, $CS_{3MT2}=1.34 \pm 0.06$ m.s⁻¹) (mean change=-0.009, 95% CI: -0.02 to 0.002, $t_{(10)}=-1.80$, $p=0.102$). There was a nearly perfect and significant positive ICC in CS between the two 3MT trials ($r=0.97$, 95% CI: 0.89 to 0.99, $p<0.0001$). Similarly, there were no significant differences in D' between the two 3MT trials ($D'_{3MT1}=18.36 \pm 4.07$ m, $D'_{3MT2}=17.54 \pm 3.11$ m) (mean change=0.82, 95% CI: -0.58 to 2.22, $t_{(10)}=1.31$, $p=0.221$). There was a very large and significant positive ICC in D' between the two 3MT trials ($r=0.87$, 95% CI: 0.58 to 0.96, $p=0.001$). The CV between the two 3MT trials was 0.9% for CS (95% CI: 0.6 to 1.6%) and 9.1% for D' (95% CI: 6.3 to 16.5%). The raw and standardised TE of the CS between the two 3MT trials was 0.01 m.s⁻¹ (95% CI: 0.01 to 0.02 m.s⁻¹) and 0.20 (small) (95% CI: 0.14 to 0.35), respectively. The raw and standardised TE of the D' between the two tests was 1.47 m (95% CI: 1.03 to 2.59 m) and 0.45 (small) (95% CI: 0.31 to 0.78), respectively.

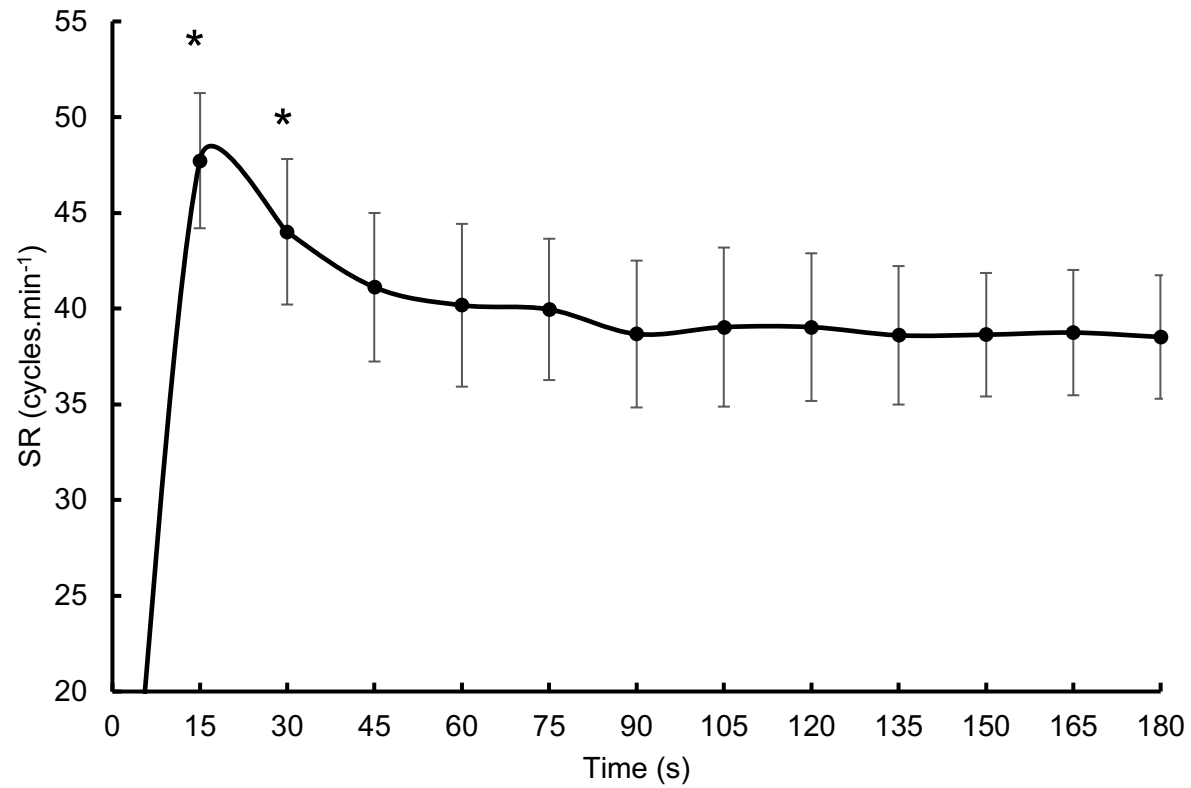


Figure 3.5. The group mean stroke rate-time profile of the 3-min all-out test.

* $p < 0.05$ compared to the stroke rate in the last 30 s, $n=12$.

Table 3.3. Test-retest reliability of the 3-min all-out swimming tests.

	3MT₁	3MT₂	CV (%)	ICC (α)	Raw TE (Std)	95% CI
CS (m.s⁻¹)	1.34 ± 0.06	1.34 ± 0.06	0.9	0.97*	0.01 (0.20)	-0.02 to 0.002
D' (m)	18.36 ± 4.07	17.54 ± 3.11	9.1	0.87*	1.47 (0.45)	-0.58 to 2.22
speed for 150 s (m.s⁻¹)	1.46 ± 0.06	1.46 ± 0.06	0.6	0.98*	0.01 (0.15)	-0.01 to 0.01
speed for 180 s (m.s⁻¹)	1.44 ± 0.06	1.44 ± 0.06	0.6	0.98*	0.01 (0.15)	-0.02 to 0.004
SR (cycles.min⁻¹)	41.20 ± 2.87	41.13 ± 3.58	2.6	0.91*	1.07 (0.35)	-0.95 to 1.08

CV, coefficient of variation; ICC, intra-class correlation coefficient; TE, typical error; Std, standardised; CI, confidence interval; CS, critical speed; D', finite work capacity above critical speed; SR, stroke rate; n=11; * $p < 0.05$

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

3.5 Discussion

The principal finding of this study is that the CS derived from the 3MT is comparable to the CS derived from conventional models, supporting our first hypothesis. D' values from 3MT were lower compared to the conventional methods, which is contrary to our second hypothesis. Additionally, the 3MT method showed high test-retest reliability in both CS and D' . To our knowledge, this is the first study that has assessed concurrent and predictive validity and examined the test-retest reliability of the 3MT in highly-trained swimmers.

3.5.1 Validity and test-retest reliability

The CS from the 3MT test was almost identical and correlated nearly perfectly with the CS derived from the conventional models, extending findings from previous studies conducted in cycling (Vanhatalo, Doust, Burnley, 2007), running (Broxterman et al., 2013; De Aguiar et al., 2018), rowing (Cheng et al., 2012), and swimming (Tsai and Thomas, 2017). The SEE in this study ($0.02 \text{ m}\cdot\text{s}^{-1}$, 1.5 % of $\text{CS}_{3\text{MT}}$) was lower compared to the SEE previously reported for CS in swimmers ($0.11 \text{ m}\cdot\text{s}^{-1}$, 12%) (Tsai and Thomas, 2017), cyclists (6-11 W, 2-5%) (Vanhatalo, Doust and Burnley, 2007; 2008) and rowers (24 W, 9%) (Cheng et al., 2012). Our finding is however in contrast with Mitchell et al. (2018a) who reported higher CS derived from the modified 3MT (12 x 25 m) compared to the CS derived from two TT in highly-trained swimmers. The difference between CS values in this study could be attributed to the methodology employed. Specifically, the authors excluded the turns in order to improve reliability of the 3MT test and allowed ~ 5 s rest between each 25 m, which is different compared to the traditional 3MT that is performed continuously and with turns that become increasingly more difficult to execute as swimmers perform the test. Indeed, the rest of ~ 5 s could arguably allow sufficient time for swimmers to adjust their feet on the wall and maximise their push-off the wall every 25 m, recover some level of D' , and/or reduce some level of fatigue and technique impairment, consequently elevating CS (Ferguson et al., 2010; Oliveira et al., 2012). The difference between CS derived from modified 3MT and TT would be potentially greater if this study included trials longer than 100 and 200 m that have been previously shown to overestimate CS by 7.8% (Dekerle et al., 2002). Although, Mitchell et al. (2018a) reported improved reliability of the 3MT test compared to previous studies, the authors acknowledged that

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

exclusion of turns and inclusion of the rest period could have an impact on the ability of the modified 3MT test to accurately estimate training speeds/times that are typically prescribed and performed with turns.

An additional important finding from the present study was that D'_{3MT} was $\sim 14\%$ lower in comparison to D'_{CM} . This is consistent with previous studies in swimming ($\sim 32.7\%$; Tsai and Thomas, 2017), cycling ($\sim 4.5\%$; Vanhatalo, Doust, Burnley, 2007) and running ($\sim 30.9\%$; Broxterman et al., 2013; $\sim 16\%$; De Aguiar et al., 2018), but is in contrast with Mitchell et al. (2018a) and Cheng et al. (2012) who reported $\sim 8.7\%$ and $\sim 30.1\%$ higher D'_{3MT} compared to D' derived from conventional methods in highly-trained swimmers and rowers, respectively. Considering the findings from Ferguson et al. (2010) that examined impact of recovery duration from prior high-intensity exercise on W' recovery, the higher D' values derived from the modified swimming 3MT could be attributed to the ~ 5 s passive rest between each 25 m (total of ~ 55 s of rest), that could have artificially inflated values of D' . This difference could have been reduced, if the authors chose TT distances longer than 200 m that have been shown to provide more accurate estimation of D' in multiple sports, including swimming (Dekerle et al., 2002). We found a very large correlation between D'_{3MT} and D'_{CM} ($r=0.79$) and SEE of 4.01 m between D'_{3MT} and D'_{DT} ($\sim 20.6\%$ of the mean D'_{3MT}) and 3.71 m between D'_{3MT} and $D'_{1/T}$ ($\sim 19\%$ of the mean D'_{3MT}). This is similar to the findings of Vanhatalo, Doust and Burnley (2007), who observed a very large correlation between work done above the end power (WEP) and W' ($r=0.84$), and a SEE value of 2.8 kJ or $\sim 18.7\%$ of the mean WEP. This is however contrary to studies in rowing and swimming (Cheng et al., 2012; Tsai and Thomas, 2017), which reported a weak relationship between D'_{3MT} and D'_{CM} . Indeed, SEE for D' in our study was lower compared to Tsai and Thomas (2017) who reported a SEE of 6.41 m (36.4% of D'_{3MT}) between 3MT and DT, and 4.49 m (25.5% of D'_{3MT}) between 3MT and 1/T. The higher SEE for CS and D' in the study of Tsai and Thomas (2017) compared to the current study could be related to the following procedures employed by Tsai and Thomas (2017): 1) Recreational swimmers with a wide range of swimming abilities (SD range of TT 12.0-127.6 s), and with the difference between highest and lowest CS values of $0.39 \text{ m}\cdot\text{s}^{-1}$ ($0.71\text{-}1.10 \text{ m}\cdot\text{s}^{-1}$) were recruited. This is significantly greater than in the present study, where the SD range for TT was 5.54-24.29 s and the difference between the highest and lowest CS recorded was substantially lower (0.17

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

m.s⁻¹, 1.25-1.42 m.s⁻¹); 2) The omission of familiarisation with 3MT and TT distances, recently emphasised by Triska et al. (2017) as necessary for optimising validity (reduced SEE for CP by ~30% and for W' by ~50% after familiarisation) and reliability (CV for CP decreased by 1.5% i.e. 4.1 vs 2.6%; for W' by 17.1% i.e. 25.3 vs 8.2% after familiarisation) of the critical power/speed concept parameters in highly-trained subjects that also showed lower CP and notably higher W' values when familiarisation with conventional method was not performed; 3) Use of primary (TT) and secondary data (online race results) that were performed with a push off start and dive, respectively, and were not adjusted as the authors argued that differences between dive and a push off start would cause meaningless differences of 2-4% in D' i.e., 0.22-1.2 m, however the 0.87 s measurement they referred to was taken from the study that used national performance swimmers (Takeda et al., 2009), therefore the actual differences between the push-off and dive start could have created meaningful difference in the investigated values in these swimmers; 4) The subjects completed inconsistent ratios of TT to race results used for derivation of CS and D' in conventional models; and 5) The subjects completed inconsistent warm-ups that included differences in duration and intensity, that have been previously emphasised as fundamental aspects to control for in order to minimise any impact of prior exercise on D' values and recovery (Vanhatalo and Jones, 2009; Ferguson et al., 2010).

Whether the D'_{CM} and D'_{3MT} represent the same physiological quantity is still under debate (Johnson et al., 2011; Burnley, 2009). Indeed, Johnson et al. (2011) suggested that the disparity of D' might be related to the unexplained variance in either method of determining D'/W'. Additionally, based on accumulating evidence, it seems that the D'/W' may not be a simple 'anaerobic capacity' parameter solely determined by stores of intramuscular substrates as originally thought, but it has been also linked to the $\dot{V}O_2$ slow component and fatigue-related metabolites (H⁺, P_i, ADP, extracellular K⁺) (Jones et al., 2010; Ferguson et al., 2010), that behaviour might differ between all-out and TT exercise (Vanhatalo et al., 2011, Bailey et al., 2016). Additionally, Green and Dawson (1993) suggested that 'anaerobic capacity' is a theoretical construct and measuring it in units of work may be prone to measurement errors, making it difficult to investigate the D' concept. Current research suggests D' as a more variable measure compared to CS (Pettitt, 2016; Johnson et al., 2011; Ferguson et al., 2010; Vanhatalo and Jones, 2009; Vanhatalo, Doust, Burnley, 2008b). Previous research has noted the sensitivity

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

of D' to nutrition (Miura et al., 2000), cadence (Vanhatalo, Doust and Burnley, 2008b), prior high-intensity exercise ($CS_{<}$) (Ferguson et al., 2007; Heubert et al., 2005), interval duration (Mattioni Maturana et al., 2018; Triska et al., 2018; Hill, 1993), choice of TT or TTE method (Coakley and Passfield, 2018; Karsten et al., 2018), inter-trial recovery (Karsten et al., 2017), implementation of familiarisation (Triska et al., 2017) and even to mental fatigue (Salam, Marcora, Hopker, 2018). Whether, the conventional method represents the gold standard method for the estimation of D' in swimming is questionable. The original method for deriving CS and D' from the conventional models is based on the assumption that the energy cost of transport is constant as speed increases (di Prampero et al., 2008; di Prampero, 1999). Considering the exponential relationship that exists between speed and energy expenditure in swimming due to the drag swimmers encounter as well as changes in stroke efficiency and mechanics (di Prampero et al., 2008; Capelli, Pendergast, Termin, 1998; Dekerle et al. 2005b), defining parameters of the CS concept using this method might be problematic in swimming and could have contributed to differences between D' values derived from 3MT and conventional protocol. Indeed, Tsai and Thomas (2017) attributed the lower values of D' in 3MT to the exponential increase in energetic cost with speed that translated to a quicker decline in speed and shorter time in reaching asymptotic speed that led to a smaller D' . Similarly to Tsai and Thomas (2017), we observed a significant short but rapid decrease in speed in the first 60 s which could indeed be a plausible explanation for lower D'_{3MT} values in our study too.

Alternatively, although participants in this study were encouraged to come to the TT prepared and the intensity of the warm-up was low to minimise any impact of prior exercise on D' , day-to-day variability associated with TT, could have had an impact on the size of D'_{CM} . Johnson et al. (2011) suggested that the conventional method of determining W' is more prone to high variability due to the extension of trials over multiple days, and suggested the 3MT as more reliable method of assessing W' . Indeed, in the present study there were no significant differences in the parameters tested between two 3MT trials and high test-retest reliability was observed ($ICC=0.87-0.98$), in agreement with Johnson et al. (2011), Wright, Bruce-Low and Jobson (2017), Cheng et al. (2012), De Aguiar et al. (2018) and Mitchell et al. (2018a) that examined test-retest reliability of 3MT in cycling, rowing, running and swimming respectively. Moreover, CV values in our study were 0.9% for CS and 9.1% for D' , which is similar

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

to Mitchell et al. (2018a) (CS: 1.1%; D': 5.7%) Burnley, Doust and Vanhatalo (2006) (CP: 3%), Vanhatalo (2008) (W': 9%) and Wright, Bruce-Low and Jobson (2017) (CP: 1.17, 1.93%; W': 5.39, 8.44%), and both fall into acceptable ranges (CS: <5%; D': <10%) recently used by Triska et al. (2017). Our CV were lower when compared to Johnson et al. (2011) (CP: 6.7%; W': 20.7%) and Cheng et al. (2012) (CP: 6.3%; W': 18.4%). Although, CV values for CS and D' were lower in this study, the CV for D' was higher when compared to CS. This confirms findings from previous studies that have suggested D' as a more sensitive variable compared to CS. Considering the factors D' is sensitive to and their relationship to preparedness of athletes to train, although not investigated to date, D' could perhaps represent a parameter that could be utilised for optimising monitoring and prescription of training.

The use of TT, as opposed to TTE for derivation of CS and D' in conventional method is still under debate and could also have been a reason for a difference in D' between the two methods used in this study (Coakley and Passfield, 2018; Karsten et al., 2018; Triska et al., 2017). Although the group of swimmers were used to swimming the distances used for calculation of CS and D' in the conventional method, some swimmers could have struggled with longer TT distances. Indeed, when D' profiles were assessed on an individual basis there was a greater discrepancy in D' derived from the 3MT and the conventional method in swimmers specialising in shorter distances (50, 100, 200 m) in comparison to long distances (400, 800, 1500 m). Most of the races in swimming are performed over 50, 100, 200 m distances and most of the swimmers in our study very rarely raced or trained at distances longer than 200 m except for the four swimmers that specialised in 400, 800 and/or 1500 m races. Therefore, as the short distance swimmers were not as familiarised with the swimming distances greater than 200 m this could be a reason for the D' discrepancy between the methods. Indeed, the recent study of Triska et al. (2017) found that familiarisation with TT increased CP by ~3.5% and notably decreased W' by ~13% in highly-trained subjects. The authors therefore recommended familiarisation with TT for optimal derivation of CP and W' in the conventional methods. Interestingly, we also observed a ~14% difference in D' between 3MT and conventional methods, therefore the omission of familiarisation with TT could have been a factor contributing to this difference in the current study.

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

Furthermore, potential factors that could have contributed to discrepancies in D' between the 3MT and conventional methods could be related to stroke mechanics, namely SR. The SR in 3MT (40.62 ± 3.37 cycles.min⁻¹) was significantly higher compared to the 400 m (37.70 ± 4.05 cycles.min⁻¹), 600 m (36.78 ± 4.01 cycles.min⁻¹) and 800 m (36.59 ± 4.20 cycles.min⁻¹) TT. To our knowledge, the impact of SR on D' has not been investigated in swimming to date, but based on the previous research studies investigating the impact of cadence on parameters of the CP concept, a potential explanation for the lower D' values in 3MT could be related to higher SR observed in 3MT. Indeed, Vanhatalo, Doust and Burnley (2008b) examined the impact of high and low cadence on W' values in trained subjects and found that the W' was significantly higher in the low cadence trials, and lower in the high cadence trials. The authors concluded that W' is sensitive to even relatively minor changes in cadence. This is somewhat in agreement with previous studies that examined an influence of stroke mechanic on the energy cost in swimming (Barbosa et al., 2008; Wakayoshi et al., 1995) and found that whilst SR might increase propulsion, it also leads to a disproportionate increase in energy expenditure and oxygen consumption (Barbosa et al., 2008; Wakayoshi et al., 1995; Counsilman, 1973). Indeed, in the present study, a rapid speed decline in the first 60 s of the 3MT coincided with the decline in SR, and could therefore contribute to a plausible explanation for lower D' derived from 3MT.

Finally, although D'_{3MT} was lower compared to D'_{CM} , when the calculation for predictive TT times was modelled with CS_{3MT} , the predicted times were consistent with those actually performed. On average, the time difference between actual and predicted TT was 1.23 ± 2.06 s (0.09-5.05), 2.06 ± 3.30 s (0.15-8.6), 1.06 ± 6.67 s (0.30-14.40) and 1.33 ± 6.47 (1.13-14.40) s for 200, 400, 600 and 800 m TT, respectively. This is lower compared to those reported in the Vanhatalo, Doust and Burnley (2007) study (i.e., ~11-28 s).

3.5.2 The 3-min all-out test profile

The peak speed values observed in this study were reached at ~10-15 s, consistent with the previous research studies (Vanhatalo, Doust, Burnley, 2007; Burnley, 2009; Cheng et al., 2012; Broxterman et al., 2013; Tsai and Thomas, 2017). Moreover, the results of the present study showed that the speed during the 3MT declined rapidly over the first 60 s and reached relatively stable levels in the last 120 s. Previous studies have

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

found a significant decrease in work rate to 135 s in cycling (Vanhatalo, Doust, Burnley, 2007), 150 s in rowing (Cheng et al., 2012) and 60 s in swimming (Tsai and Thomas, 2017). The possible explanation for differences in the 3MT profiles could be related to the differences in bioenergetics between the modes of exercise. Indeed, Sousa et al. (2015a) attributed differences in bioenergetics of highly-trained cyclists, runners, rowers and swimmers to the type and size of the active muscle mass, body position adopted and muscle contraction regimen. Considering this, the possible explanation for an earlier decrease and stabilisation in swimming speed could be attributed to the following: 1) substantially lower proportion of type I muscle fibres (i.e. higher proportion of more fatiguing type II muscle fibres) in the upper body compared to lower body (Johnson et al., 1973), that swimmers predominantly use to generate propulsive forces; 2) greater muscle mass utilised in swimming; 3) lower economy of movement, and therefore larger energy expenditure as a result of the water environment being ~800 times denser than the air (di Prampero, 1986); 4) restricted breathing during swimming and turns as well as limited ability to produce maximal muscle contractions due to the constraints of water environment (Sousa et al., 2015a) and; 5) larger O₂ deficit related to a longer time constant in swimming (i.e., slower $\dot{V}O_2$ kinetics) (Sousa et al., 2015a), previously attributed to lower muscle perfusion, increased venous return but reduced blood hydrostatic pressure in legs as a result of the horizontal position adopted by swimmers (Libicz, Roels and Millet, 2005; Koga et al., 1999). Although our findings of a significant decrease in speed in the first 60 s are consistent with Tsai and Thomas (2017), our finding related to the stabilisation of speed are inconsistent. Specifically, Tsai and Thomas (2017) observed the stabilisation of speed in the last 90 s i.e., 30 s later than in the current study. This is somewhat surprising considering that we used highly proficient swimmers compared to Tsai and Thomas (2017) study. However, considering that the relationship between speed and the energy cost in swimming is exponential as a result of the hydrodynamic drag swimmers encounter (Capelli, Pendergast, Termin, 1998), this could provide a justification for the differences observed. Tsai and Thomas (2017) study recruited participants with a lower level of swimming abilities compared to our study. Indeed, the peak speed achieved ($1.36 \pm 0.18 \text{ m}\cdot\text{s}^{-1}$) is similar to the CS of the subjects in the present study ($1.33 \pm 0.06 \text{ m}\cdot\text{s}^{-1}$). Therefore, as the swimmers in the present study swam at higher speeds throughout the 3MT, the drag encountered by these subjects

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

was higher, which could have led to higher energy expenditure and therefore fatigue occurred at earlier stages in the 3MT. This is somewhat in agreement with the work of Fernandes et al. (2008) and Fernandes et al. (2006) who examined TTE at $v\dot{V}O_{2\max}$ between low-level and highly-trained swimmers and found that highly-trained swimmers sustained $v\dot{V}O_{2\max}$ for a shorter period of time (~76.5 s) compared to low-level swimmers. One of the main factors the authors attributed this finding to was the higher energy cost associated with the swimming speeds and drag encountered by the highly-trained swimmers. In addition, as a result of the stabilisation of speed in the last 90 s, Tsai and Thomas (2017) suggested that a test of 135 s is sufficient to estimate CS and D' in swimming. However, caution must be taken with this interpretation, as the stabilisation of speed in some subjects, especially those with greater D' values, occurred at later stages in the 3MT, potentially risking inaccurate estimation of CS and D'.

3.6 Practical applications

One of the main practical advantages of the 3MT is its ability to accurately demarcate CS in a single test. Although the variables derived from 3MT represent physiological phenomenon, these concepts are fundamentally based on performance and require minimal data analysis, expertise and resources, making it accessible to a broad spectrum of applied practitioners (Vanhatalo, Jones and Burnley, 2011). The applications of 3MT are broad and include assessment of physical fitness, athlete selection, the prediction of performances as well as design of optimal warm-up, pacing and racing strategies (Pettitt, 2016). The parameters derived from 3MT may also enable coaches to prescribe individualised high intensity training sessions with quantitative goals that are challenging yet attainable, thereby minimising likelihood of overtraining, as well as serving as a useful motivational tool for athletes. Additionally, considering that both CS and D' are sensitive to hypoxia (i.e., are reduced) (Townsend et al., 2017), except for utilising 3MT to optimise training in normoxia, 3MT could be used to optimise and normalise training intensity at altitude training camps without a need to complete multiple trials spread across several days, thereby reducing chances for mismanagement of training loads.

From a different perspective, although not validated against traditional methods, the stabilisation of the SR in the last 30 s of the 3MT could be used for identification of

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

the critical stroke rate (CSR) that has been proposed by Dekerle et al. (2002) as the highest SR that can be maintained for an extended period of time. Considering the importance of employing optimal SR and SL, that combination has implication on swimming economy and speed (Barbosa et al., 2008), CSR derived from 3MT could be used alongside CS to inform and optimise both technical and physiological components of swimming that are fundamentally interrelated in this sport. Indeed, according to Dekerle et al. (2005b), Barden and Kell (2009) and Pelarigo et al. (2016), CS and MLSS do not only represent physiological transition thresholds between heavy and severe exercise intensity domains but also biomechanical boundaries beyond which stroke mechanics become compromised. Therefore, integration of technical work at this intensity or above could represent a very useful tool for coaches to replicate racing scenarios in which swimmers aim to sustain the highest speed and technical proficiency. To achieve this, training sets could be prescribed with an aim to maintain CS with a lower SR than CSR, or maintain CSR while swimming faster than CS. This would require adoption of greater SL that has been identified by previous research studies as the most critical factor in achieving superior performance of elite swimmers when compared to their less efficient counterparts (Arellano et al., 1994; Smith, Norris and Hogg, 2002). Indeed, the 3MT method allows complex assessment of the parameters related directly to performance that have functional meaning and have real-world use in a short space of time (Smith, Norris and Hogg, 2002). More recently, power-duration-based training intensity zones have been demarcated using CP from 3MT in cycling, emphasising the potential of this test to demarcate physiological domains of exercise intensity in a single test (Francis et al., 2010). Given that this approach from cycling can now be applied to swimming, future swimming research should explore these methods as a means of providing enhanced prescription and testing methods compared to those currently used in swimming practice (Smith, Norris and Hogg, 2002). Additionally, based on the latest study of Courtright et al. (2016), which focused on optimising training prescription in swimming using the 3MT, this test has the potential to facilitate a shift in the perception that high training volumes are a requirement for success in swimming. High volumes of swimming training have been identified as a cause for a wide array of overuse injuries (Tovin, 2006) and burnout (Raedeke, Lunney and Venables, 2002) in swimmers, and so the 3MT has the potential to improve these training practices in swimming. Finally, given that the validity of 3MT has been previously assessed in cycling and running, and the

Chapter 3: Validity and reliability of the 3-min all-out test in national and international competitive swimmers

present study assessed the validity of the 3MT in swimming, multidisciplinary sports such as triathlon can obtain values of CS/CP and D'/W' in all three disciplines in a shorter period of time, compared to those typically needed to establish these parameters.

3.7 Conclusion

In conclusion, this is the first study to demonstrate that the 3MT is a valid and reliable alternative protocol to estimate CS concept parameters in highly-trained swimmers. Although, the 3MT provided a reliable estimate of D' , it is recommended that future studies examine the relationship between D' derived from both methods and the factors influencing this complex parameter. The demonstrated concurrent and predictive validity of the 3MT test in swimming represents a potential for the more widespread use of the CS concept, as its application in a swimming field has not been extensively applied and fully maximised to date. This could therefore represent a very fruitful area of interest for researchers as well as athletes, coaches and sports practitioners working in swimming.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Chapter 4: Demarcating exercise intensity domains in swimming; Is there an alternative to incremental step test and beats below HR_{MAX} method?

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4.1 Abstract

Purpose: Firstly, to establish if the critical speed (CS) derived from the 3-min all-out test (3MT) can be used to estimate boundaries of exercise intensity domains compared to those derived from an incremental step test (IST). Secondly, to assess the accuracy of the 50-40 and 30-20 ‘beats below maximal heart rate’ (BBM) method, currently utilised by swimming coaches to demarcate boundaries between moderate-heavy and heavy-severe exercise, respectively. **Methods:** Thirteen highly-trained swimmers completed an IST and 3MT in freestyle to establish speeds at: lactate threshold (LT), lactate turnpoint (LTP), maximum aerobic speed (S_{MAX}), and CS. **Results:** Using linear regression through the origin, speeds at LT, LTP and S_{MAX} were predicted at 89%, 98% and 103.5% of CS derived from 3MT. There were no significant differences between threshold speeds derived from IST and 3MT ($p>0.05$), and nearly perfect correlations at LT (1.21 ± 0.06 ; $1.21 \pm 0.06 \text{ m.s}^{-1}$; $r=0.92$), and LTP (1.33 ± 0.07 ; $1.33 \pm 0.07 \text{ m.s}^{-1}$; $r=0.90$), and very large correlations at S_{MAX} (1.40 ± 0.06 ; $1.40 \pm 0.07 \text{ m.s}^{-1}$; $r=0.88$; all $p<0.0001$). Speeds estimated at 50 ($1.11 \pm 0.08 \text{ m.s}^{-1}$) and 40 BBM ($1.17 \pm 0.07 \text{ m.s}^{-1}$) were lower compared to LT, and speeds estimated at 30 ($1.23 \pm 0.07 \text{ m.s}^{-1}$) and 20 BBM ($1.29 \pm 0.07 \text{ m.s}^{-1}$) were lower compared to LTP and CS (all $p<0.02$). **Conclusion:** The 3MT can be used as an alternative to an IST to estimate boundaries of exercise intensity domains, in practical settings where resources or time might be limited. However, the BBM method significantly underestimates the speed at LT, LTP and CS in highly-trained swimmers.

Key words: critical speed, 3-minute all-out, testing, training, swimming

4.2 Introduction

In sports science and practice, exercise intensity has traditionally been prescribed using intensity zones based on a distinct heart rate (HR), blood lactate concentration

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

[La⁻] and/or oxygen uptake ($\dot{V}O_2$) associated with specific work rate. It is now well established that the exercise intensity continuum comprises of four exercise intensity domains: moderate, heavy, severe, and extreme, each of which is demarcated by well-established physiological parameters and elicit distinct physiological responses to exercise (Burnley and Jones, 2007). The moderate domain represents the work rates below the lactate threshold (LT) or gas exchange threshold (GET). Within this domain, there is no change or only a transient increase in [La⁻], and $\dot{V}O_2$ attains a steady state within 2-3 minutes in healthy individuals (Burnley and Jones, 2007). The lower boundary of heavy domain is demarcated by LT/GET whilst critical speed (CS) or maximal lactate steady state (MLSS) represent the upper boundary of this domain, although other parameters such as lactate turnpoint (LTP), individual anaerobic threshold (IAT) or respiratory compensation point (RCP) have been utilised (Faude, Kindermann and Meyer, 2009; Pessoa Filho et al., 2012). Exercise in the heavy domain is accompanied by elevated [La⁻] and development of a $\dot{V}O_2$ slow component that typically achieves a delayed steady state in 10-20 minutes (Burnley and Jones, 2007). The severe domain encompasses the work rates above CS but below the highest work rate that elicits maximum oxygen uptake ($\dot{V}O_{2MAX}$). A steady state in [La⁻] and $\dot{V}O_2$ can no longer be achieved in this domain, which eventually drives $\dot{V}O_2$ to its maximum and exhaustion occurs soon thereafter. The extreme domain represents the work rates at which exhaustion ensues before $\dot{V}O_{2MAX}$ has been attained (Hill, Poole and Smith, 2002). Although coaches utilise five or more training intensity zones, the fundamental basis of these zones are grounded in the four exercise intensity domains described above.

The traditional approach to demarcating exercise intensity domains in swimming research involves completion of a 7 x 200 m incremental step test (IST) in which 200 m stages and 0.05 m.s⁻¹ increments are based on the speed associated with a given athlete's personal best time (PB) for 200 m or 400 m event or time trial (TT) (Fernandes et al., 2008; 2011). Alternatively, a 7 x 200 m protocol where 200 m PB time plus 30 s is sequentially subtracted by 5 s to determine target time at each stage have been utilised (Pyne, Lee and Swanwick, 2001). During an IST, HR, [La⁻] and $\dot{V}O_2$ data are typically collected. However, due to the resources, time and expertise required to implement this invasive test, an IST is not regularly performed by coaches coaching larger groups of swimmers. Instead, generalised prescription of training

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

zones based on a fixed percentage (%HR_{MAX}) or a number of beats below maximal HR (BBM), obtained via maximal exercise or age-predictive equations is widespread practice amongst swimming coaches. This is perhaps most likely due to the lower cost and expertise required to apply this method to multiple swimmers and on a regular basis (see **Table 4.1**). However, considering the inter- and intra-individual differences in the way athletes respond to exercise (Meyer, Gabriel and Kindermann, 1999; Bagger, Petersen and Pedersen, 2003), the effectiveness of the methods that utilise maximal HR (HR_{MAX}) alone to individualise training has been questioned (Meyer, Gabriel and Kindermann, 1999; Sarzynski et al., 2013; Robergs and Landwehr, 2002).

Table 4.1. Training intensity measurement utilised by swimming coaches, national training centres and delivered as a part of the swimming coaching curriculums.

Zones	Name	Description	HR (bbm)	La (mM)	RPE
Z 1	A1	<i>Aerobic Low Intensity</i> Base conditioning and technical training; warm-up and warm-down; Predominantly Fat Metabolism; largely slow-twitch fiber recruitment	> 50	< 2	< 9
	A2	<i>Aerobic Maintenance/ Development</i> Base aerobic training Improves cardio-respiratory system; enhances Lactate Removal	40-50	2-4	10-12
Z 2	AT	<i>Anaerobic Threshold</i> Maximal Lactate Steady State where Lactate production = Lactate removal; Optimal intensity for development of aerobic capacity	20-30	3-6	14-15
Z 3	VO ₂	<i>Aerobic Overload</i> High intensity work at approximately VO _{2max} ; This type of training includes Heart Rate and Vcrit sets; Improves VO _{2max} and aerobic power	5-20	6-12	17-19
Z 4	LP	<i>Lactate Production</i> Training intensity results in the maximal speed of lactate build up; This type of training includes Race Pace training; Enhances rate of glycolytic energy production	5-15	8-15	17-19
	LT	<i>Lactate Tolerance</i> High intensity work with medium rest to improve buffering; Developing the ability to tolerate lactate/ acidity in the muscle	0-10	12-20	19-20
Z5	Speed	<i>Sprinting –ATP-PC</i> High intensity, short duration, long rest repeats Designed to improve alactic energy production (ATP-PC), neuromuscular coordination and fast-twitch muscle fiber recruitment	N/A	N/A	N/A

bbm, beats below maximal heart rate of an individual; maximal heart rate is typically obtained via a maximal exercise, or the following equations: “220-age” Fox et al. (1971), “208-(0.7 x age)” Tanaka et al. (2001); adapted from Peyrebrune (2005).

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Recently, a 3-min all-out test (3MT) has been proposed to demarcate the boundary between heavy and severe exercise intensity domains (Burnley, Doust and Vanhatalo, 2006). The 3MT requires a subject to complete an all-out effort from the beginning of the test which is sufficient to maximise contribution of the finite capacity above CS (D') in the first 150 s, and therefore the average speed in the last 30 s should correspond to CS. Indeed, mean work rate in the last 30 s of the 3MT has been shown to correspond with CP/CS derived from conventional testing methods in multiple sports (Vanhatalo, Doust, Burnley, 2007; Broxterman et al., 2013; Cheng et al., 2012), including swimming (Piatrikova et al., 2018; Tsai and Thomas, 2017). The 3MT test provides an estimate of CS in a single test as opposed to the conventional protocols that require a subject to complete multiple time-to-exhaustion or TT over several days. Indeed, the simplicity of the 3MT test has allowed broader application of the CS concept in monitoring and prescription of training in multiple sports (Jones and Vanhatalo, 2017; Pettitt, 2016).

To extend the utility of the 3MT, Francis et al. (2010) recently utilised the CP from the 3MT to estimate the boundary between moderate and heavy exercise intensity domains in competitive cyclists. Lactate threshold was approximated at 76% of CP in this study, and this finding was confirmed in the subsequent study by Johnson et al. (2011). However, this estimation was in contrast with the findings of Pettitt, Jamnick and Clark (2012), who observed GET at 90% of running CS. The authors attributed this inconsistency to differences in mechanical efficiency between running and cycling. Thus, considering the inherent differences in the bioenergetics of swimming compared to other modes of exercise (Sousa et al., 2015a; Greco et al., 2013), the estimation of LT derived from swimming CS is likely to vary from those previously reported in cycling and running. Indeed, the relationships between the parameters derived from the 3MT and other physiological parameters have not been investigated to date in swimming. Given the time-consuming and invasive nature of an IST, alongside the multidisciplinary nature of swimming as well as the technological constraints that apply to physiological testing in swimming, obtaining reliable estimates of all exercise intensity domains without the need for blood sampling and in a single test would be appealing to swimming practitioners, and could also represent a more effective and efficient alternative to BBM method.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Therefore, the aim of this study was to assess whether the CS derived from 3MT can be utilised to estimate the parameters demarcating the exercise intensity domains, when compared to those established in an IST. Based on previous findings (Francis et al., 2010), we hypothesised that the 3MT could be used to estimate the boundaries of the exercise intensity domains in a single test. The second aim of this study was to examine the accuracy of the 50-40 and 30-20 BBM methods that are currently utilised by swimming coaches to demarcate the boundary between moderate-heavy and heavy-severe exercise intensity domains, respectively.

4.3 Methods

4.3.1 Participants

A performance squad of 13 swimmers (6 males, 7 females, age 16 ± 1 yrs, weight 63.7 ± 8.9 kg, height 175 ± 8 cm) volunteered to participate in this study, which had received approval from the Research Ethics Approval Committee for Health at the University of Bath. All subjects were competitive swimmers that regularly competed in one or more national or international events per year, completed a training volume of ~ 45 km.week⁻¹, ($\sim 8-9$ swimming sessions, 2-3 land sessions.week⁻¹), and had training histories of 8 ± 2 yrs. The participants had no known history of respiratory, cardiovascular, metabolic or musculoskeletal disease, and were not taking any medications that might have affected the variables under investigation. Prior to any testing all subjects and parents filled out a Physical Activity Readiness Questionnaire and were informed of the protocol, risks and discomfort associated with the procedure and potential benefits, both verbally and in writing, and gave their written consent.

4.3.2 Experimental design

The protocol consisted of four visits to the swimming pool. Firstly, the subjects performed a 200 m TT that was utilised for the prescription of speed increments in the IST. As the subjects in this study regularly performed 3MT as a part of their performance evaluation, the subjects were not asked to complete a familiarisation trial for this test. All swimmers completed a familiarisation trial with the IST. On the following visits on separate days, subjects performed the IST and 3MT in a random order over a one-week period. Each trial was preceded by a 5-min warm up at low intensity to minimize an impact of prior exercise on D' (Jones et al., 2010; Vanhatalo

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

and Jones, 2009) and was followed by 5-min rest. The front crawl technique was adopted in all tests. All trials were completed in a 50 m pool using a push-off start, flip turns, and occurred at the same time of the day (± 1 h) in order to minimize an impact of circadian variation on performance (Drust et al., 2005). Subjects swam in their own one-piece swimsuit, swim cap and goggles throughout the testing period. Given the potential impact of nutrition and preceding exercise on the $[La^-]$ values (Faude, Kindermann and Meyer, 2009), all subjects and parents were provided with an information sheet explaining optimal nutrition and recovery strategies to maximise results of the testing. Training volume and intensity were reduced in the week of testing and all subjects had a recovery session the evening prior to testing and had the morning off on the day of testing.

4.3.3 Incremental step test

Resting $[La^-]$ and HR values were collected in the last minute of the resting period. The first stage of the test started at the speed corresponding to the speed at 200 m TT minus $0.35 \text{ m}\cdot\text{s}^{-1}$, and was increased in the subsequent stages by $0.05 \text{ m}\cdot\text{s}^{-1}$ until exhaustion occurred (Adapted from Fernandes et al., 2008; 2011). In-between 200 m steps, a 30 s rest interval was allowed for blood sampling ($[La^-]$ from an earlobe) and adjustment of the pace for the subsequent stage. Pace was controlled with a Finis Tempo Trainer (Finis Inc., California, USA) that was preprogrammed to the pace required to swim each 50 m in order to ensure that the swimmers swam their expected 200 m time evenly. The swimmers were instructed to be at each wall on the bleep of the tempo trainer to ensure that the predetermined pace was followed throughout each stage. Time to complete each 200 m stage (Finis Inc., 3 x 100 m, California, USA), $[La^-]$ (Lactate Plus, Nova Biomedical, Waltham, USA), rating of perceived exertion (RPE, 1-10 Borg scale) and HR (A300, Polar, USA) were collected at the end of each 200 m stage. A swimmer was considered exhausted when their actual swimming time was more than 2 seconds slower than their 200 m target time.

4.3.4 Three-min all-out test

The test started with one minute of standing rest before a subject was given a 10 s warning prior to a push-off start. Subjects were asked to swim at an ‘all out’ swimming speed i.e. “as fast as you possible can at any given time during the test”. This is important to emphasise as pacing could confound results in this test (Jones et al.,

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

2010). Swimming time splits were recorded using a stopwatch (Finis, 3 x 100 m, California, USA) at every 10 m as the swimmer's head was visualized passing the cone. Ten meters stages were marked with fluorescent cones placed parallel to the swimmer's lane at every 5 m along the pool deck to enable calculating split times as well as displacement (D) of the swimmer at 150 s and 180 s. A 10 s countdown was given to the researcher that walked with a cone alongside a swimmer and placed a cone at 150 s and 180 s at the furthest point reached (i.e., a hand). Distance at 150 s (D_{150}) and 180 s (D_{180}) were recorded using a 50 meters tape measure placed parallel to the swimming lane and were used for the calculation of CS using the following equation (Courtright et al., 2016):

Equation 4.1

$$CS_{3MT} = (D_{180} - D_{150})/30$$

The $[La^-]$ was collected at the end of the test. Strong verbal encouragement was provided throughout the tests, and time to complete each trial and incremental 200 m stage was recorded to the nearest hundredth of a second or cm in the case of displacement. Subjects were not informed of the elapsed time or their performance to prevent pacing. A visual inspection of each swimmer's speed-time 3MT profile was conducted to identify any occurrence of pacing, the subjects that paced were asked to repeat the 3MT again on a different day.

4.3.5 Determination of threshold speeds from IST

The swimmers' $[La^-]$ -velocity curves were constructed to obtain the following parameters:

1. LT_{IST} : was defined as the point at which $[La^-]$ started and continued to increase above the baseline concentration, via visual inspection from three independent researchers (Burnley and Jones, 2007)
2. LTP_{IST} : was defined as the point at which $[La^-]$ started to increase exponentially, via visual inspection from three independent researchers in combination with a mathematical model suggested by Machado et al. (2006) and Fernandes et al. (2011)
3. $S_{MAX-IST}$: was defined as the highest speed of the 200 m stage in the IST
4. % Δ : difference between the speed at LT_{IST} and $S_{MAX-IST}$

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

4.3.6 Determination of threshold speeds from the CS_{3MT}

Following the approach utilised by Francis et al. (2010), the equation utilised to predict speed at LT_{3MT}, LTP_{3MT} and S_{MAX-3MT} was derived via linear regression through the origin between CS_{3MT} and LT_{IST}, LTP_{IST} and S_{MAX-IST}, respectively. Specifically, linear regression between CS_{3MT} and each exercise intensity threshold speed derived from the IST was restricted to cross through the origin (i.e., intercept was set to zero), and resulting equations were used to calculate predicted thresholds speeds for each swimmer utilising their CS derived from 3MT (e.g., regression equation: $y = 0.8931x$, where x is CS_{3MT} of participant and y is the point of interest [e.g. predicted LT speed], and slope can be interpreted as a percentage value if multiplied by 100).

4.3.7 Determination of threshold speeds from the BBM method

The highest HR recorded during the IST was used as a HR_{MAX}. According to the method of Peyrebrune (2005) described in the **Table 4.1**, HR_{MAX} was subsequently utilised to demarcate the boundary between moderate-heavy domains using 50 (LT_{50BBM}) and 40 BBM (LT_{40BBM}), and between heavy-severe domains using 30 (LTP_{30BBM} / CS_{30BBM}) and 20 BBM (LTP_{20BBM} / CS_{20BBM}). To estimate the HR associated with LT_{50BBM}, LT_{40BBM}, LTP_{30BBM} and LTP_{20BBM}, HR_{MAX} was subtracted by 50, 40, 30 and 20, respectively. To estimate the threshold speeds associated with the investigated BBM methods, a regression equation describing the linear relationship between HR and speed was utilised.

4.3.8 Statistical analyses

Statistical analyses were performed using SPSS Version 24.0 (SPSS Inc., Chicago, IL). One-way repeated-measures ANOVA was used to determine differences between CS_{3MT}, speed at LT_{IST}, LTP_{IST}, and S_{MAX-IST}. Main effects were compared using the Bonferroni correction. Bivariate correlation analysis was performed between CS_{3MT} and speed at LT_{IST}, LTP_{IST} and S_{MAX-IST}. Differences between actual and predicted speeds at LT, LTP, CS and S_{MAX} were determined using paired-sample t-test. A Pearson correlation coefficient and a Bland-Altman analysis were also used to assess the relationships, bias and the limits of agreement (LOA) between actual and predicted speeds at LT, LTP, CS and S_{MAX}, as well as actual and predicted HR at LT and LTP when using the BBM methods. The alternative method to the IST was considered significantly biased if the 95% confidence intervals (CI) for mean bias did not cross

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

over zero. The acceptable LOA were defined *a priori* as 2% of the mean speed at LT, LTP, CS and S_{MAX}, based on our practical experience of the acceptable level of precision for coaches prescribing target times within training sessions (± 1.5 s for 100 m split). The acceptable LOA were defined as 3% of the mean HR at LT and LTP (Bagger, Petersen, Pedersen, 2003; Buchheit, 2014). Default thresholds for correlations were 0.1, small; 0.3, moderate; 0.5, large; 0.7, very large; 0.9, nearly perfect (Hopkins, 2002a). Default magnitude thresholds for the standardised standard error of estimate (SEE_{STD}) were <0.1, trivial; 0.1-0.3, small; 0.3-0.6, moderate; 0.6-1.0, large; 1.0-2.0, very large; >2.0, extremely large (Hopkins, 2015). Effect size (ES) was calculated using Cohen's *d* (i.e., mean difference divided by pooled SD). For all tests, statistical significance was accepted at the $p < 0.05$ level, with data presented as means \pm SD.

4.4 Results

Mean speed data and pairwise comparisons for significant differences between the speed at LT_{IST}, LTP_{IST}, CS_{3MT} and S_{MAX-IST} are shown in **Table 4.2**. The speed at LT_{IST}, LTP_{IST}, and CS_{3MT} were 86%, 95% and 96% of S_{MAX-IST}, respectively. The CS_{3MT} and LTP_{IST} occurred at 76 ± 14 and $62 \pm 12\%$ Δ , respectively. There was no significant difference between speed at LTP_{IST} and CS_{3MT} ($p = 0.119$), and the mean bias was 0.02 ± 0.03 m.s⁻¹ (95% CI: 0.004 to 0.04 m.s⁻¹). The 95% LOA between the speed at LTP_{IST} and CS_{3MT} ranged from -0.04 to 0.08 m.s⁻¹ (± 0.06 m.s⁻¹), which is outside of the 2% threshold determined *a priori* as acceptable (2% threshold: ± 0.03 m.s⁻¹). **Table 4.2** also shows percentages of CS_{3MT} that were used to predict speed at LT_{3MT}, LTP_{3MT} and S_{MAX-3MT} for each swimmer.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Table 4.2. Comparisons of the speed measures derived from the incremental step test and 3-min all-out test.

	speed (m.s ⁻¹)	[La ⁻] (mmol.L ⁻¹)	HR (bpm)	<i>r</i> with CS _{3MT}	prediction (% of CS _{3MT})
LT_{IST}	1.21 ± 0.06	1.32 ± 0.40	164 ± 12	0.92*	89.31
LTP_{IST}	1.33 ± 0.07†	3.98 ± 1.12	185 ± 10	0.90*	98.27
S_{MAX-IST}	1.40 ± 0.06‡	10.73 ± 2.04	197 ± 8	0.88*	103.51
CS_{3MT}	1.35 ± 0.07†	11.22 ± 1.37	-	-	-

LT, lactate threshold; LTP, lactate turnpoint; S_{MAX}, maximum aerobic speed derived from the incremental step test (IST); CS, critical speed derived from the 3-min all-out test (3MT); [La⁻], blood lactate; HR, heart rate; bpm, beats per minute; † $p < 0.0001$ compared to LT_{IST}; ‡ $p < 0.001$ compared to all speed measures, * $p < 0.0001$ correlation (r); model fit (R^2) for linear regression through the origin was 0.85, 0.82 and 0.68 for LT, LTP and S_{MAX}, respectively.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

4.4.1 Defining boundaries of exercise intensity domains using CS_{3MT}

The mean predicted speeds at LT_{3MT}, LTP_{3MT} and S_{MAX-3MT} when using CS derived from 3MT are presented in **Table 4.3** alongside SEE, 95% CI, ES, correlation, bias and 95% LOA. **Figure 4.1** demonstrates relationships and bias \pm 95% LOA between the threshold speeds derived from the IST and 3MT.

4.4.1.1 Lactate threshold

There was no significant difference ($p=0.99$), and nearly perfect correlation between the speed at LT_{IST} and LT_{3MT} ($p<0.0001$). SEE_{RAW} was 0.03 m.s⁻¹ (95% CI: 0.02 to 0.04 m.s⁻¹, 2.2% of mean LT), and SEE_{STD} was moderate (0.42, 95% CI: 0.22 to 0.88). Mean bias between the speed at LT_{IST} and LT_{3MT} was -0.00004 ± 0.02 m.s⁻¹ (95% CI: -0.01 to 0.01 m.s⁻¹). The 95% LOA between the speed at LT_{IST} and LT_{3MT} were outside the 2% threshold determined *a priori* as acceptable (2% threshold: ± 0.02 m.s⁻¹), however 10 out of 13 swimmers were within this threshold.

4.4.1.2 Lactate turnpoint

There was no significant difference ($p=1.00$), and nearly perfect correlation between the speed at LTP_{IST} and LTP_{3MT} ($p<0.0001$). SEE_{RAW} was 0.03 m.s⁻¹ (95% CI: 0.02 to 0.06 m.s⁻¹, 2.6% of mean LTP), and SEE_{STD} was moderate (0.48, 95% CI: 0.25 to 1.02). The mean bias between the speed at LTP_{IST} and LTP_{3MT} was -0.000001 ± 0.03 m.s⁻¹ (95% CI: -0.02 to 0.02 m.s⁻¹). The 95% LOA between the speed at LTP_{IST} and LTP_{3MT} were outside of the 2% threshold determined *a priori* as acceptable (2% threshold: ± 0.03 m.s⁻¹), however 9 out of 13 swimmers were within this threshold.

4.4.1.3 Maximum aerobic speed

There was no significant difference ($p=0.93$), and very large correlation between S_{MAX-IST} and S_{MAX-3MT} ($p<0.0001$). SEE_{RAW} was 0.03 m.s⁻¹ (95% CI: 0.02 to 0.05 m.s⁻¹; 2.1% of mean S_{MAX}), and SEE_{STD} was moderate (0.54, 95% CI: 0.28 to 1.19). The mean bias between S_{MAX-IST} and S_{MAX-3MT} was -0.001 ± 0.03 m.s⁻¹ (95% CI: -0.02 to 0.02 m.s⁻¹). The 95% LOA between S_{MAX-IST} and S_{MAX-3MT} were outside of the 2% threshold determined *a priori* as acceptable (2% threshold= ± 0.03 m.s⁻¹), however, 10 out of 13 swimmers were within this threshold.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Table 4.3. Comparisons of the speeds at lactate threshold, lactate turnpoint and maximum aerobic speed derived from 3-min all-out test and the incremental step test.

	Speed (m.s ⁻¹)	95% CI	ES	SEE _{RAW} (SEE _{STD})	<i>r</i> (95% CI)	Bias ± SD	95% LOA
LT_{3MT} v LT_{IST}	1.21 ± 0.06	-0.01 to 0.01	-0.002	0.03 (0.42)	0.92*(0.75 to 0.98)	-0.00004 ± 0.02	-0.05 to 0.05†
LTP_{3MT} v LTP_{IST}	1.33 ± 0.07	-0.02 to 0.02	0.00	0.03 (0.48)	0.90*(0.70 to 0.97)	-0.000001 ± 0.03	-0.06 to 0.06†
S_{MAX-3MT} v S_{MAX-IST}	1.40 ± 0.07	-0.02 to 0.02	-0.02	0.03 (0.54)	0.88*(0.64 to 0.96)	-0.001 ± 0.03	-0.07 to 0.06†

LT, lactate threshold; LTP, lactate turnpoint; S_{MAX}, maximum aerobic speed; IST, incremental step test; 3MT, 3-min all-out test; **p*<0.0001 correlation (*r*); † limits of agreement (LOA) outside of the acceptable threshold of 2%; SEE_{RAW}, raw standard error of estimate; SEE_{STD}, standardised standard error of estimate; ES, effect size; CI, confidence interval.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

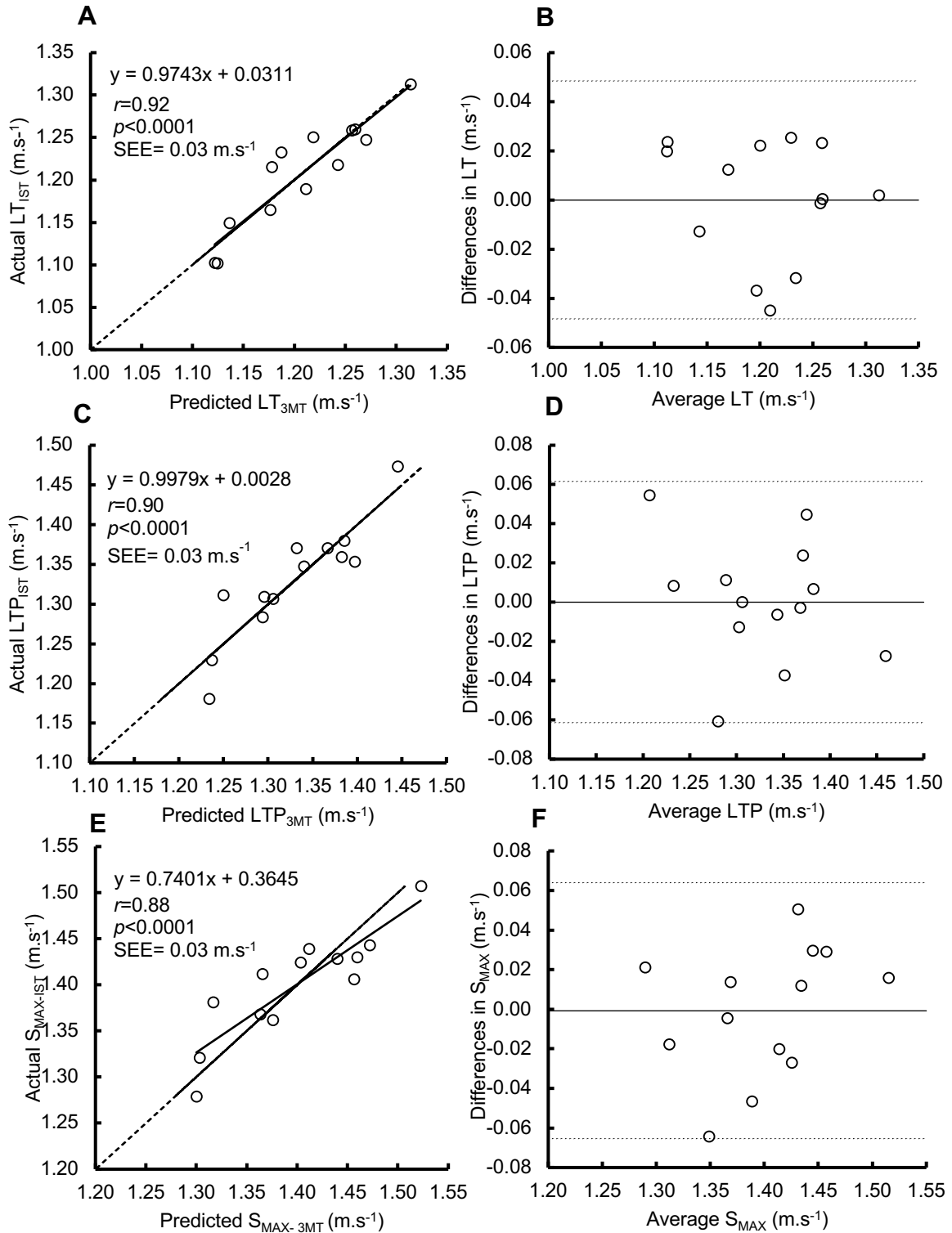


Figure 4.1. Correlation and Bland-Altman analyses for differences in lactate threshold (A,B), lactate turnpoint (C,D) and maximal aerobic speed (E,F) derived from the incremental step test and the 3-min all-out test. In the panels A, C and E, the solid line is the line of best-fit linear regression, the dashed line is the line of identity. In the panels B, D and F, the solid lines represent the mean difference between LT_{IST} - LT_{3MT}, LTP_{IST} - LTP_{3MT}, S_{MAX-IST} - S_{MAX-3MT}, respectively, the dashed lines represent the 95% LOA; n=13.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

4.4.2 Defining boundaries of exercise intensity domains using the BBM method

The mean predicted speeds at LT, LTP and CS, and mean predicted HR at LT and LTP derived from the investigated BBM methods are illustrated in **Table 4.4** and **Table 4.5** alongside SEE, 95% CI, ES, correlation, bias and 95% LOA, respectively. **Figure 4.2** illustrates the individual relationships between the threshold speeds derived from the IST (LT_{IST}, LTP_{IST}) and 3MT (CS_{3MT}), and investigated BBM.

4.4.2.1 Speed at lactate threshold

The individual intensities based on 50 and 40 BBM expressed relative to LT_{IST} were $92 \pm 5\%$ (range 83-100%) and $97 \pm 5\%$ (89-104%) of LT_{IST}, respectively. There was a significant difference between speeds at LT_{50, 40BBM} and LT_{IST} ($p < 0.02$), but large correlations were found in-between ($p < 0.03$). The LT_{50BBM} and LT_{40BBM} significantly underestimated the speed at LT_{IST} ($p < 0.05$), and the 95% LOA were outside of the 2% threshold determined *a priori* as acceptable (2% threshold: $\pm 0.02 \text{ m}\cdot\text{s}^{-1}$).

4.4.2.2 Critical speed

The individual intensities corresponding to 30 and 20 BBM and expressed relative to CS_{3MT} were $91 \pm 4\%$ (84-98%) and $95 \pm 3\%$ (89-101%) of CS_{3MT}, respectively. There was a significant difference between speeds at CS_{30, 20BBM} and CS_{3MT} ($p < 0.0001$), but very large correlations were found in-between ($p < 0.003$). The CS_{30BBM} and CS_{20BBM} significantly underestimated the CS_{3MT} ($p < 0.05$), and the 95% LOA were outside of the 2% threshold determined *a priori* as acceptable (2% threshold: $\pm 0.03 \text{ m}\cdot\text{s}^{-1}$).

4.4.2.3 Speed at lactate turnpoint

The individual intensities corresponding to 30 and 20 BBM and expressed relative to LTP_{IST} were $92 \pm 3\%$ (87-96%) and $97 \pm 2\%$ (93-102%) of LTP_{IST}, respectively. There was a significant difference between speeds at LTP_{30, 20BBM} and LTP_{IST} ($p < 0.001$), but very large correlations were found in-between ($p < 0.0001$). The LTP_{30BBM} and LTP_{20BBM} significantly underestimated the speed at LTP_{IST} ($p < 0.05$), and the 95% LOA were outside of the 2% threshold determined *a priori* as acceptable (2% threshold: $\pm 0.03 \text{ m}\cdot\text{s}^{-1}$).

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Table 4.4. Comparisons of the speed at lactate threshold, lactate turnpoint and critical speed derived from the incremental step test and 3-min all-out test to the beats below HR_{MAX} method.

	Speed (m.s ⁻¹)	95% CI	ES	SEE _{RAW} (SEE _{STD})	<i>r</i> (95% CI)	Bias ± SD	95% LOA
LT_{50BBM} v LT_{IST}	1.11 ± 0.08*	0.06 to 0.14	-1.44	0.05 (1.25)	0.63 ^a (0.11 to 0.87)	-0.10 ± 0.06 ^b	-0.23 to 0.02 ^c
LT_{40BBM} v LT_{IST}	1.17 ± 0.07*	0.01 to 0.08	-0.60	0.05 (1.09)	0.68 ^a (0.20 to 0.89)	-0.04 ± 0.06 ^b	-0.15 to 0.07 ^c
CS_{30BBM} v CS_{3MT}	1.23 ± 0.07‡	0.10 to 0.15	-1.82	0.05 (0.86)	0.76 ^a (0.36 to 0.92)	-0.12 ± 0.05 ^b	-0.22 to -0.03 ^c
CS_{20BBM} v CS_{3MT}	1.29 ± 0.07‡	0.04 to 0.09	-0.96	0.04 (0.79)	0.79 ^a (0.41 to 0.93)	-0.06 ± 0.04 ^b	-0.15 to 0.02 ^c
LTP_{30BBM} v LTP_{IST}	1.23 ± 0.07†	0.08 to 0.12	-1.41	0.04 (0.57)	0.87 ^a (0.61 to 0.96)	-0.10 ± 0.04 ^b	-0.17 to -0.03 ^c
LTP_{20BBM} v LTP_{IST}	1.29 ± 0.07†	0.02 to 0.06	-0.57	0.03 (0.51)	0.89 ^a (0.67 to 0.97)	-0.04 ± 0.03 ^b	-0.10 to 0.02 ^c

LT, lactate threshold; LTP, lactate turnpoint; CS, critical speed; IST, incremental step test; 3MT, 3-min all-out test; 40 and 50 beats below maximal heart rate (BBM) were used to derive the speed at LT; 20 and 30 BBM were used to derive the speed at LTP and CS; * $p < 0.02$ compared to LT_{IST}; † $p < 0.001$ compared to LTP_{IST}; ‡ $p < 0.0001$ compared to CS_{3MT}; ^a $p < 0.03$ correlation (r); ^b $p < 0.05$ significantly biased, ^c limits of agreement (LOA) outside of the acceptable threshold of 2%; SEE_{RAW}, raw standard error of estimate; SEE_{STD}, standardised standard error of estimate; ES, effect size; CI, confidence interval.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

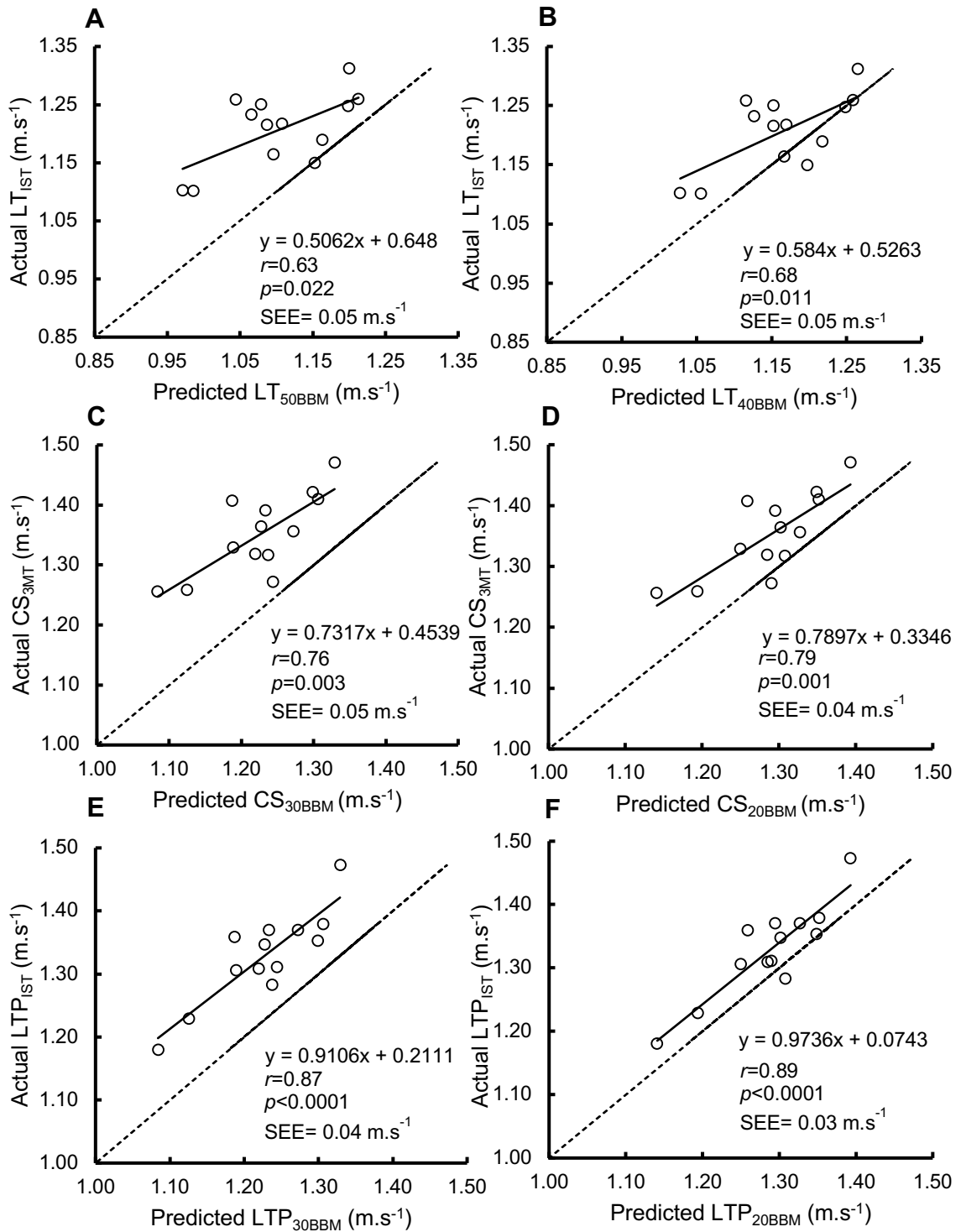


Figure 4.2. Actual versus predicted speed at (A, B) lactate threshold, (C, D) critical speed, (E, F) lactate turnpoint, using the beats below HR_{MAX} method. The solid line is the line of best-fit linear regression and the dashed line is the line of identity; n=13.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

4.4.2.4 Heart rate at lactate threshold

The individual HR corresponding to 50 and 40 BBM and expressed relative to LT_{IST} were $90 \pm 5\%$ (82-99%) and $96 \pm 5\%$ (88-105%) of LT_{IST}, respectively. There was a significant difference between HR at LT_{50, 40BBM} and LT_{IST} ($p < 0.03$), but large correlations were found in-between ($p = 0.019$). The LT_{50BBM} and LT_{40BBM} significantly underestimated the HR at LT_{IST} ($p < 0.05$), and the 95% LOA were outside of the 3% threshold determined *a priori* as acceptable (3% threshold: ± 5 bpm).

4.4.2.5 Heart rate at lactate turnpoint

The individual HR corresponding to 30 and 20 BBM and expressed relative to LTP_{IST} were $91 \pm 3\%$ (88-97%) and $96 \pm 3\%$ (93-103%) of LTP_{IST}, respectively. There was a significant difference between HR at LTP_{30, 20BBM} and LTP_{IST} ($p < 0.0001$), but very large correlations were found in-between ($p < 0.0001$). The LTP_{30BBM} and LTP_{20BBM} significantly underestimated the HR at LTP_{IST} ($p < 0.05$), and the 95% LOA were outside of the 3% threshold determined *a priori* as acceptable (3% threshold: ± 5 bpm).

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Table 4.5. Comparisons of the heart rate at lactate threshold and lactate turnpoint derived from the incremental step test and the beats below HR_{MAX} method.

	HR (bpm)	95% CI	ES	SEE _{RAW} (SEE _{STD})	<i>r</i> (95% CI)	Bias ± SD	95% LOA
LT_{50BBM} v LT_{IST}	147 ± 8*	11 to 22	-1.62	10 (1.21)	0.64 ^a (0.13 to 0.88)	-17 ± 9 ^b	-35 to 2 ^c
LT_{40BBM} v LT_{IST}	157 ± 8*	1 to 12	-0.63	10 (1.21)	0.64 ^a (0.13 to 0.88)	-7 ± 9 ^b	-25 to 12 ^c
LTP_{30BBM} v LTP_{IST}	167 ± 8†	14 to 20	-1.91	6 (0.66)	0.84 ^a (0.53 to 0.95)	-17 ± 5 ^b	-28 to -7 ^c
LTP_{20BBM} v LTP_{IST}	177 ± 8†	4 to 10	-0.79	6 (0.66)	0.84 ^a (0.53 to 0.95)	-7 ± 5 ^b	-18 to 4 ^c

LT, lactate threshold; LTP, lactate turnpoint; IST, incremental step test; 40 and 50 BBM were used to derive the heart rate (HR) at LT; 20 and 30 BBM were used to derive the HR at LTP; * $p < 0.03$ compared to LT_{IST}, † $p < 0.0001$ compared to LTP_{IST}; ^a $p < 0.02$ correlation (r); ^b $p < 0.05$ significantly biased; ^climits of agreement (LOA) outside of the acceptable threshold of 3%; bpm, beat per minute; SEE_{RAW}, raw standard error of estimate, SEE_{STD}, standardised standard error of estimate; ES, effect size; CI, confidence interval.

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

4.5 Discussion

The principal finding of this study is that the CS derived from the 3MT can be used to estimate the boundaries of exercise intensity domains that are comparable to those derived from an IST in competitive swimmers. Additionally, the commonly-used BBM method significantly underestimated speed at LT_{IST}, CS_{3MT} and LTP_{IST}, and HR at LT_{IST} and LTP_{IST}. When expressed individually in relation to the LT_{IST}, CS_{3MT} and LTP_{IST}, the investigated BBM methods covered wide ranges of exercise intensities that might be unacceptable in swimming, where the range between exercise intensity domains is narrow (Greco et al., 2013). To our knowledge this is the first study to examine the utility of the 3MT to establish the exercise intensity boundaries, or to assess the accuracy of the BBM method to demarcate exercise intensity domains in swimming.

4.5.1 Defining boundaries of exercise intensity domains using CS_{3MT}

4.5.1.1 Moderate-heavy exercise intensity domains

Using linear regression through the origin between CS_{3MT} and the speed at LT_{IST}, this study found that the speed at LT could be predicted at 89.31% of CS_{3MT} with a low SEE (0.03 m.s⁻¹; 2.2% of LT). This is in contrast with Francis et al. (2010) who predicted the power output at LT at 76% of CP_{3MT} with prediction error of 28 W (15% of LT) in 16 competitive cyclists. Considering the inherent differences between cycling and swimming, the differences in the LT prediction estimate between the present study and Francis et al. (2010) study could be attributed to differences in bioenergetics between these modes of exercise (Sousa et al., 2015a). Indeed, Greco et al. (2013) was the first study that examined the range of speeds demarcating the exercise intensity domains in trained swimmers, and found that this range is very narrow in swimming. In this study, the speed at LT occurred at 95% of MLSS, and MLSS occurred at 88% of S_{MAX}. Indeed, this equated to a difference of only 0.22 m.s⁻¹ (~16 s per 100 m) between LT and S_{MAX}, 0.06 m.s⁻¹ (~5 s per 100m) between LT and MLSS, and 0.16 m.s⁻¹ (~11 s per 100 m) between MLSS and S_{MAX}. The authors attributed this finding to the energy cost of swimming, which is not constant with the speed. Instead, their relationship is exponential due to the drag the swimmers encounter and changes in stroke efficiency as speed increases and fatigue develops (Figueiredo et al., 2011, Capelli, Pendergast and Termin, 1998; Dekerle et al., 2005b;

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Barden and Kell, 2009; Pelarigo et al., 2016; Chatard, Lavoie and Lacour, 1990), consequently narrowing the range of exercise intensity domains in swimming. The narrow range between exercise intensity domains in swimming found by Greco et al. (2013) was confirmed in the present study, equating to a difference of $0.19 \text{ m}\cdot\text{s}^{-1}$ ($\sim 11 \text{ s per } 100 \text{ m}$) between the speed at LT_{IST} and S_{MAX-IST}. The speed at LT_{IST} expressed relative to the boundary between heavy and severe domains, however, differed between the present study (89% of CS_{3MT}) and the study of Greco et al. (2013) (95% of MLSS). The differences could be attributed to the protocol utilized to establish this boundary. Indeed, whilst Greco et al. (2013) utilized a traditional MLSS protocol, the 3MT was completed in the present study. We did not conduct the MLSS protocol to establish differences between MLSS and CS_{3MT}, however, considering the previous findings from Dekerle et al. (2005a) and De Lucas et al. (2012) that reported that CS occurs $\sim 5.6\%$ higher compared to MLSS in swimming and running, respectively, adjusting the speed at MLSS reported in Greco et al. (2013) by 5.6% would result in a similar position of LT in relation to the adjusted MLSS speed as in the present study (i.e., 90%).

Similarly to Greco et al. (2013), the speed at LT_{IST} occurred at 86% of S_{MAX-IST} in the present study, which is however different to the position of LT when expressed in relation to $\dot{V}O_{2\text{MAX}}$ in active, moderately-trained population (i.e., 50-65% of $\dot{V}O_{2\text{MAX}}$) (Poole et al., 2016). Although we were unable to measure $\dot{V}O_2$ in this study, our findings suggest that our highly-trained, though not elite swimmers would be able to sustain a high percentage of their $\dot{V}O_{2\text{MAX}}$, similar to those reported in elite runners (i.e., 70-90% of $\dot{V}O_{2\text{MAX}}$) (Joyner and Coyle, 2008). Instead of attributing this to the level of swimmers recruited, Greco et al. (2013) attributed this finding to the horizontal position adopted by swimmers and the constant hydrostatic pressure from the micro-gravitational environment of water that could alter blood volume distribution, stroke volume, cardiac output and local blood flow that are likely to increase oxidative capacity (i.e., blood lactate removal) (Pendergast and Lundgren, 2009).

4.5.1.2 Heavy-severe exercise intensity domains

On average, the CS_{3MT} and LTP_{IST} occurred at 96% and 95% of S_{MAX-IST}, or 76 % Δ and 62% Δ , respectively. Using linear regression through the origin, the present study

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

suggests that if LTP is of interest rather than CS, 98.27% of CS_{3MT} could be used to estimate the speed at LTP, with a low SEE ($0.03 \text{ m}\cdot\text{s}^{-1}$; 2.6% of LTP). Considering that LTP_{IST} and CS_{3MT} are frequently utilized to demarcate the boundary between heavy and severe domains, we examined their relationship, as the research examining the difference between these parameters is scarce in swimming. There was no significant difference, and nearly perfect correlation between LTP_{IST} and CS_{3MT}. However, the LOA were not within the acceptable threshold of 2%, and LTP_{IST} occurred at $0.02 \text{ m}\cdot\text{s}^{-1}$ (~1.5%) lower when compared to CS_{3MT}. This finding could be attributed to differences in the protocols employed to demarcate the boundary separating the heavy from severe exercise intensity domain. Indeed, the recent publication of Clark et al. (2018) found that the boundary between heavy and severe domains, as demarcated by 3MT, was reduced by 8% following 2 h of a heavy-intensity exercise bout, suggesting that the parameter that was believed to be relatively robust to prior exercise actually differs in fatigued compared to rested state. Whilst the recruited swimmers completed less amount of the time in the heavy intensity domain (~2.5-7 min) compared to Clark et al. (2018), the time the swimmers spent in the heavy domain before LTP_{IST} was reached could have been sufficient to induce some level of fatigue, and affect stroke efficiency, consequently leading to a 1.5% reduction in the speed at LTP_{IST} (Oliveira et al., 2012). The impact of the protocol on the thresholds obtained is in agreement with Dekerle et al. (2003), who compared power outputs associated with MLSS, CP and RCP, and attributed the differences between the work rates to the protocols employed, as well as to the physiological variables utilised to establish these workloads. Indeed, to establish the LTP from the IST and the CS from an all-out test requires different physiological and psychological adaptations to the protocol's constraints, and whilst LTP_{IST} depends on the blood lactate measurement, CS_{3MT} is solely based on the average speed in last 30 s of the 3MT test. These factors could therefore provide an explanation for the differences observed between the speed at LTP_{IST} and CS_{3MT}.

In contrast with the study of Greco et al. (2013), the present study found CS_{3MT} at a higher percentage of S_{MAX-IST} (96% vs. 88%) as well as % Δ (76% Δ vs 26 % Δ). As discussed previously, these differences could be attributed to the protocol utilised to establish the boundary between heavy-severe domains. Indeed, after the adjustment utilised previously (i.e., 5.6%), this would result in similar values compared to those

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

reported in highly-trained swimmers, but still higher values compared to Greco et al. (2013) (i.e., 91% of S_{MAX} and 35% Δ) (Fernandes et al., 2008; Pelarigo et al., 2016). Considering the exponential relationship between the energy cost and swimming speed, we could expect the values of CS_{3MT} and LTP_{IST} expressed in relation to $S_{MAX-IST}$ and as % Δ to be greater compared to those typically reported in healthy, moderately-trained population (i.e. 70-80% $\dot{V}O_{2MAX}$) and in cycling or running (i.e., 50% Δ), respectively (Poole et al., 2016). Indeed, the position of both CS_{3MT} and LTP_{IST} in relation to $S_{MAX-IST}$ was above those reported in highly-trained runners (80-90% $\dot{V}O_{2MAX}$), but similar to those reported in highly-trained swimmers (92-96% of S_{MAX}), consequently resulting in 76% Δ and 62% Δ in this study, respectively (Poole et al., 2016; Dekerle, 2006; Fernandes et al., 2008; Dekerle et al., 2010). Additionally, considering that MLSS, CS and anaerobic threshold do not only represent a physiological transition threshold between heavy and severe domains, but also a biomechanical boundary beyond which the stroke mechanics have been shown to become compromised (i.e., stroke rate increases non-linearly, stroke length decreases significantly) (Dekerle et al., 2005b; Barden and Kell, 2009; Oliveira et al., 2012; Pelarigo et al., 2016; Figueiredo et al., 2011; Wakayoshi et al., 1995; Keskinen and Komi, 1993), this could further increase the energy cost of swimming with speed once swimmers pass this threshold, consequently narrowing the range between CS_{3MT}/LTP_{IST} and $S_{MAX-IST}$ further.

4.5.1.3 Severe-extreme exercise intensity domains

The S_{MAX} was predicted to occur at 103.51 % of CS_{3MT} with a low SEE (0.03 m.s⁻¹ or 2.1%). This finding is similar to Francis et al. (2010), who reported that $\dot{V}O_2$ peak power could be predicted at 105% of CP_{3MT} . This is however in contrast with Greco et al. (2013), who reported S_{MAX} at 114.5% of MLSS. This difference could be attributed to the fact that the speed at MLSS generally occurs at a lower level compared to CS, as discussed previously, or to the fact that Greco et al. (2013) utilised a 400 m TT protocol without any prior fatiguing exercise to establish S_{MAX} . Alternatively, the difference could be attributed to the level of swimmers recruited. Specifically, based on the average speeds associated with LT (1.08 ± 0.09 m.s⁻¹), MLSS (1.14 ± 0.08 m.s⁻¹) and S_{MAX} (1.30 ± 0.09 m.s⁻¹) reported by Greco et al. (2013), the present study recruited a higher standard of competitive swimmers. Given that more highly-trained

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

subjects tend to display LT and CS at a higher percentage of $\dot{V}O_{2MAX}$, and tend to possess greater technical ability, both of which affect the energy cost of swimming, the level of participants recruited could explain differences in the position of the parameters demarcating the exercise intensity domains between Greco et al. (2013) and the present study (Poole et al., 2016; Pelarigo et al., 2016). Further studies are required to elucidate differences between CS_{3MT} and MLSS, the position of the parameters demarcating the spectrum of exercise intensities into domains in swimming, as well as how the performance level of swimmers affects the position of these parameters.

4.5.2 The “beats below HR_{MAX}” method

Following the prescription approach commonly utilised by swimming coaches, this study demonstrated that the BBM methods provide an inaccurate estimation of the boundaries demarcating both moderate-heavy and heavy-severe exercise intensity domains. Despite large correlations found, neither 50 nor 40 BBM provided acceptable demarcation of the speed and HR associated with LT_{IST}, equating to a difference of ~8 s and ~3 s slower times per 100 m, or 17 and 7 bpm lower HR when compared to LT_{IST}, respectively. Similarly, neither 30 nor 20 BBM provided an acceptable estimate of the speed associated with LTP_{IST} and CS_{3MT}, or HR associated with LTP_{IST}, equating to a difference of ~7 s and ~3 s slower times per 100 m, or 17 and 7 bpm lower HR, respectively. One could argue that the reason behind lower speeds at 20 and 30 BBM compared to CS_{3MT} or LTP_{IST} is that these BBM methods refers to MLSS as the boundary between heavy and severe domains, which typically occurs ~5-6% lower compared to CS. Although this could be a case, given the findings of Dekerle et al. (2010) that demonstrated that when CS is prescribed intermittently (i.e., 10 x 400 m with ~40 s rest), which is more representative of the intermittent nature of swimming training, the CS is sustainable for ~50 min with steady state levels in blood lactate, representative of the MLSS responses. Additionally, LTP as assessed in the present study has been shown to correspond with MLSS in competitive swimmers (Fernandes et al., 2011). We therefore compared CS_{3MT} and LTP_{IST} to 20 and 30 BBM in the present study. Additionally, the difference in speeds between these BBM methods and LTP_{IST}/CS_{3MT}, on average approached 10% at 30 BBM and 5% at 20BBM, with large inter-individual differences. These findings suggest that 20 BBM

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

but not 30 BBM method could be more accurate in demarcating the boundary between heavy and severe domains, if this method is to be utilised.

The individual speeds and HR derived from the BBM method and expressed relative to LT_{IST}, LTP_{IST} and CS_{3MT} covered wide ranges (81-105%). These findings are in agreement with Meyer, Gabriel and Kindermann (1999) who recruited 36 highly-trained cyclists and triathletes in order to assess accuracy of prescribing commonly used fixed percentages of $\dot{V}O_{2MAX}$ (i.e., 75% of $\dot{V}O_{2MAX}$) and HR_{MAX} (85% of HR_{MAX}) compared to IAT. Whilst the authors found no significant difference between IAT and the power output associated with 75% of $\dot{V}O_{2MAX}$ or 85% of HR_{MAX}, wide ranges of 86 to 118% and 87 to 116% were observed, respectively. Although, the investigated BBM methods did not cover as wide ranges in the present study, considering the narrow range of exercise intensities in swimming, even slight over- or under-estimation of the boundaries demarcating the intensity domains could lead into less effective training in swimming. Specifically, athletes supposedly undertaking an identical training might in reality train either below or above LT, LTP and CS when using the investigated BBM methods. This could consequently result in different physiological response (steady or non-steady response in $[La^-]$ / $\dot{V}O_2$) and limit of tolerance, therefore leading to different training stimulus and ultimately adaptations. Additionally, considering that exercise HR can vary up to 3% (Bagger, Petersen, Pedersen, 2003; Buchheit, 2014) or 6 bpm (Lambert, Mbamba, St Clair Gibson, 1998) a day due to several factors (e.g. cardiac drift, sleep, temperature, hydration, nutrition) (Achten and Jeukendrup, 2003), this introduces further complications when training prescription is based on HR_{MAX} alone. Indeed, with less than 0.22 m.s⁻¹ (~16 s per 100 m) between the boundaries demarcating the lowest and highest exercise intensity domains, the situation of being in an undesired exercise intensity domain could likely occur with the BBM method assessed in this study. This could be amplified further if coaches choose to use age-predictive equations to calculate individual's HR_{MAX}, considering that their validity to accurately predict HR_{MAX} has been questioned in both sedentary and athletic populations (Sarzynski et al., 2013; Whyte et al., 2008; Robergs and Landwehr, 2002). Indeed, applying the equations of '220-age' and '208-0.7 x age' to the group of the recruited swimmers would result in 10 swimmers and 5 swimmers out of 13 having predicted HR_{MAX} outside of their actual HR_{MAX} range deemed as acceptable due to day-to-day variability of HR_{MAX} (i.e., ~2%, 4 bpm) (Bagger,

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

Petersen and Pedersen, 2003), respectively, with some swimmers displaying as much as 20 bpm difference between actual and predicted HR_{MAX}. From a different perspective, several studies have suggested that assuming that athletes of the same age will have identical HR_{MAX} is misleading and this was confirmed in the present study. As an example, 4 swimmers aged 16 years had a HR_{MAX} value of 184, 185, 200 and 214 bpm whilst the Fox's and Tanaka's equations would predict 204 bpm and 197 bpm, respectively (Fox et al., 1971, Tanaka et al., 2001). Therefore, the results of this study emphasise a requirement for a more precise but affordable measurement of indices demarcating exercise intensity domains compared to those currently employed by swimming coaches. Considering that individualised training becomes increasingly important as the competitive level of athletes increases, and the window of opportunity to improve decreases, the results from the present study do not support the investigated BBM method as an effective method to demarcate or prescribe exercise intensity in highly-trained swimmers. However, if this method is to be utilised, the results from the present findings suggest that the boundaries between moderate-heavy and heavy-severe domains occur at 34 ± 9 BBM (or $83 \pm 5\%$ HR_{MAX}) and 13 ± 5 BBM (or $93 \pm 3\%$ HR_{MAX}) in highly-trained swimmers, respectively.

4.6 Practical applications

Broad practical applications of the 3MT test are now well established and apply to monitoring and prescription of training as well as optimizing pacing and racing strategies (Pettitt, 2016). This study extended the utility of the 3MT, such that the parameters demarcating exercise intensity domains could be established with a single test and without the need for blood sampling. Whilst the threshold values observed in the current study (89.31 and 103.51% of the CS_{3MT} to approximate the speed at LT and the S_{MAX}, respectively) are likely to be bespoke to the standard of swimmers and swimming stroke used in this work, the process outlined in this study may be applied to other levels of swimmers/strokes in order to obtain relevant threshold values for those athletes and their specific/main stroke. The CS is directly determined from the 3MT, however if the speed at LTP (i.e., anaerobic threshold) is the point of interest instead, 98.27% of CS_{3MT} can be used. In applied settings, coaches are often limited by resource availability, time, and/or expertise, which might force them to apply less valid (but more affordable and feasible) prescription methods (e.g., the BBM method). The approach investigated in the current study could be used to enable coaches to

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

regularly obtain more robust data in large groups of swimmers in a timely manner, and without the requirement for additional equipment or expertise. It is important to note that the proposed method assumes that the speed at LT remains constant in relation to CS_{3MT} (i.e., if CS_{3MT} improves, the model assumes that the speed at LT also increases within individuals), which might not be the case and thus constitutes a limitation of this model. However, considering that the prediction equation changed minimally (<1%) when different combinations of swimmers were removed from the model, this equation is arguably still useful to predict the speed at LT on a group basis. Additionally, considering that the speed at LT is not a main predictor for competitive swimming events that last <20 min, and that most coaches have a limited amount of time and resources to establish the speed at LT on a regular basis, this model could still provide a useful estimation of the speed at LT. However, if coaches work with marathon swimmers, where LT becomes a stronger predictor of performance, a more precise measurement of the speed at LT would be recommended. Additionally, as $\dot{V}O_2$ was not collected in the present study, the minimum speed associated with $\dot{V}O_{2MAX}$ and the highest speed that elicits $\dot{V}O_{2MAX}$ could be lower and higher compared to S_{MAX}, respectively. Although this represents a limitation to the present study, the prediction equation for S_{MAX} is likely to be close to these values and thus, could be used if coaches do not have access to aquatic $\dot{V}O_2$ analysers (Buchheit and Laursen, 2013). Finally, although the approach investigated in the present study is similar to the BBM approach (i.e., estimates exercise intensity boundaries from CS only), prescribing exercise intensity relative to CS/CP has been suggested to elicit more homogenous physiological responses compared to methods such as % $\dot{V}O_{2MAX}$ or % HR_{MAX} (Jamnick et al., 2020; Muniz-Pumares et al., 2019; Lansley et al., 2011; Mann, Lamberts, Lambert, 2013). Additionally, compared to BBM method the application of the CS concept and 3MT in swimming training and performance (e.g., in prescription of personalised high intensity interval training, prediction of performance, optimising warm up/pacing strategies) is greater, more affordable and arguably more performance-related (Pettitt, 2016).

Considering the large training volumes that are typically performed in swimming (potentially to compensate for lack of individualisation), individualising training using the proposed method could allow for reduced volumes of training, which have been

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

repeatedly identified as a cause for a wide array of overuse injuries (Tovin, 2006), early specialisation and burnout (Raedeke, Lunney and Venables, 2002) in swimming. Indeed, multiple studies including the recent work of Courtright et al. (2016), have challenged the ‘high volume’ swim coaching philosophy in the last two decades (Nugent, Comyns and Warrington, 2017). Courtright et al. (2016) used the CS and D’ parameters derived from the 3MT to prescribe two sessions of high intensity interval training (HIIT) per week for four weeks in 17 competitive swimmers, whilst the swimmers engaged with their normal strength and conditioning as well as swimming skills programmes. This study found that as little as two sessions of HIIT per week with the training volume of 900-3000 yards.week⁻¹ and 40-60 min.week⁻¹ for four weeks resulted in a significantly improved CS (+0.04 m.s⁻¹), speed for the first 150 s (+0.03 m.s⁻¹) and total distance covered in 3 min (+8.64 m), which represent a significant competitive advantage in swimming. Alternatively, considering that energy expenditure increases exponentially with speed due to the drag swimmers encounter as well as deterioration in stroke efficiency (i.e. stroke rate ↑, stroke length ↓) (Dekerle et al., 2005b; Barden and Kell, 2009; Pelarigo et al., 2016; Figueiredo et al., 2011), the volume utilised to ‘fill millage’ could be instead utilised to optimise technical parameters such as swimmer’s ability to apply propulsive forces on to the water in an efficient manner. This skill becomes a progressively distinguishing factor as swimmers get closer to an elite level, and arguably represents greater capacity for improvement in athletes whose physiological capacity might be reaching its ‘ceiling’ (Pyne and Sharp, 2014; Barbosa et al., 2008). Taking into account recently published literature focused on optimising the parameters demarcating exercise intensity domains in multiple sports, including in swimming (Courtright et al., 2016; Sousa et al., 2017), future studies should apply the proposed method to highly-trained swimmers for an extended period of time (>6 weeks) in order to investigate what performance improvements, if any, can be obtained with a reduced volume of training compared to those typically observed in highly-trained swimmers (40-70 km.week⁻¹). The sessions aiming to improve the speed at LT could be prescribed with longer repetitions (400 m<) at LT speed with minimal rest, whilst 3-5 min intervals with different fractional depletion of D’ (i.e., 60-80%) and 1:1 or 1:1.5 work:rest ratio could be employed in order to improve CS and $\dot{V}O_{2MAX}$ (Pettitt, 2016). The speed associated with $\dot{V}O_{2MAX}$ and on-kinetics could also be improved by prescribing the sets at 90-

Chapter 4: Demarcating exercise intensity domains in swimming: Is there an alternative to incremental step test and beats below HR_{MAX} method?

120% of the speed associated with $\dot{V}O_{2MAX}$ with 1:1 work to rest ratio (Sousa et al., 2017; Buchheit and Laursen, 2013).

4.7 Conclusion

In conclusion, this study demonstrated that the 3-min all-out swimming test could be used to estimate the transition thresholds separating exercise intensity domains in highly-trained swimmers. Additionally, this study demonstrated that the ‘beats below HR_{MAX}’ method currently utilised by swimming coaches and delivered as a part of swim coaching curriculum, is not a suitable method to demarcate and prescribe exercise intensity in highly-trained swimmers, despite its easy-to-use nature. Indeed, with the narrow range of exercise intensities in swimming, more precise but feasible demarcation and prescription of exercise intensities compared to those currently employed in coaching practice is required. Overall, the proposed method has the potential to contribute to closing the gap between science and practice in testing and prescription of training in swimming.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

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5.1 Abstract

Purpose: To monitor physiological, technical, and performance responses to individualised high-intensity interval training (HIIT) prescribed using the critical speed (CS) and critical stroke rate (CSR) concepts in competitive swimmers completing a reduced training volume programme (≤ 30 km.week⁻¹) for 15 weeks. **Methods:** Over the 15-week period, twelve highly-trained swimmers (age: 16 ± 1 y; height: 179 ± 8 cm; weight: 66 ± 8 kg) completed four 3-min all-out tests (3MT) to determine CS and the finite capacity to work above CS (D'), and four 200 m tests at CS to establish a CSR estimate. Combining CS and D' , two HIIT sessions designed as 5 x 3 min intervals depleting 60% of D' and 3 x 3.5 min intervals depleting 80% of D' were prescribed once per week, respectively. An additional HIIT session was prescribed using CS and CSR as 10 x 150 or 200 m at CS with 2 cycles.min⁻¹ lower SR than the CSR estimate. Additional monitored variables included peak speed, average speed for 150 s (speed_{150s}) and 180 s (speed_{180s}) in 3MT, competition performance and stroke length (SL), count (SC) and index (SI) adopted by swimmers at CS. **Results:** At the end of the intervention, swimmers demonstrated faster CS (mean change \pm 90% confidence limits: $+5.4 \pm 1.6\%$), speed_{150s} ($+2.5 \pm 0.9\%$), speed_{180s} ($+3.0 \pm 0.9\%$), and higher SR ($+6.4 \pm 3.0\%$) and SI ($+4.2 \pm 3.6\%$) at CS. D' was reduced ($-25.2 \pm 7.5\%$) whilst peak speed, SL and SC changed only trivially. The change in the swimmers' personal best times in their 1st and 2nd main event was $-1.2 \pm 1.3\%$ and $-1.6 \pm 0.9\%$, respectively. **Conclusion:** HIIT programme prescribed based on the CS and CSR concepts was associated with improvements in several physiological, technical, and performance parameters in highly-trained swimmers whilst utilising a time- and resource-efficient approach. This was achieved despite a $\geq 25\%$ reduction in training volume.

Key words: 3-min all-out test, individualisation, monitoring, swimming, testing

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.2 Introduction

The overarching aim of swimming training is to enable swimmers to swim a given event in the shortest possible time. This ability is primarily determined by swimmers' physiological and technical abilities (Barbosa et al., 2008; Zacca et al., 2019a). Despite the fact that the majority of competitive swimming events last less than 5 min, swimming coaches have been known to place a great importance on the training volume to optimise these abilities (Nugent et al., 2017; Nugent, Comyns and Warrington, 2017). Indeed, swimmers are known to complete $\sim 40\text{-}70\text{ km}\cdot\text{week}^{-1}$, which can equate to $\sim 16\text{-}25\text{ h}\cdot\text{week}^{-1}$ (Nugent, Comyns and Warrington, 2017). However, a growing body of research suggests that a high-volume of low-intensity focused training provides limited performance advantage over higher-intensity, lower volume training strategies (Kilen et al., 2014; Faude et al., 2008; Nugent et al., 2017). Additionally, excessive focus on high-volume training has been linked to increased risk of overuse injuries (Sein et al., 2010), early specialisation, burnout or dropout from the sport (Lloyd et al., 2015). Recently, Nugent et al. (2017) systematically reviewed literature examining the effects of low-volume, higher-intensity training on performance in competitive swimmers and concluded that six and four out of seven eligible studies resulted in improvements of physiological and swimming performance, respectively, whilst none of these studies reported any clear decrements in performance. The authors identified only one study that explored the impact of high-intensity, low-volume training on biomechanical parameters (Termin and Pendergast, 2000). Despite the promising findings from this systematic review, the authors emphasised the limitations of the analysed studies, which were related to the short duration of the study protocols (<6.5 weeks), lack of swimming-specific methodology, and lack of focus on obtaining a combination of physiological, technical and swimming performance measures.

In competitive swimming, conducting longitudinal studies involving training interventions with sport-specific testing is challenging, given the technological and environmental constraints that apply to swimming, as well as the reservation of coaches to alter their training programmes (Buchheit, 2017; Pyne, 2016). A lack of testing methods that allow feasible and sport-specific examination of a large group of swimmers on a regular basis, could be reasons as to why coaches might not want to participate in research or apply proposed methods (Roos et al., 2013), and instead opt

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

to compromise on validity in order to use feasible approaches (Piatrikova et al., 2019). To answer the question as to whether lower volume, higher intensity programmes are effective in competitive swimming, there is a need for studies that explore these alternatives for a longer period, using more sport-specific but affordable methods, which can be used by coaches beyond research interventions.

In the last decade, the critical speed (CS) concept has become a promising applied tool utilised for testing and monitoring in multiple sports (Pettitt, 2016). More recently, the CS concept has also received attention in relation to the prescription of individualised high-intensity interval training (HIIT) (Pettitt, 2016). Whilst the minimum velocity eliciting maximum oxygen uptake ($\dot{V}O_{2\text{MAX}}$) has been used for research purposes, in swimming practice, HIIT is typically prescribed based on more affordable methods (e.g., beats below HR_{MAX} , anaerobic threshold, race-pace velocities, personal best times, holding best average), which do not take into account the between-subject differences in anaerobic and/or aerobic capacities. The CS concept may provide a solution to this problem, as it identifies CS as the boundary separating sustainable from non-sustainable exercise intensities, and D' as a finite capacity available to work above CS (Jones et al., 2010). The advantage of utilising CS and D' in HIIT prescription is that target time intervals for a given distance are based on a partial depletion of D' , relative to athlete's CS, meaning that HIIT is personalised based on indices related to the individual's physiological capacity to exercise above CS.

The CS concept is a strong predictor of swimming performance (Piatrikova et al., 2018), however, cumbersome procedures associated with determination of CS and D' via conventional protocols may have prevented wider application of this concept in swimming. Our research group has recently assessed the validity and reliability of the 3-min all-out test (3MT), which could be utilised to derive CS and D' in a more convenient manner (Piatrikova et al., 2018). Consequently, the 3MT could allow easier application of the CS concept in swimming training, where several constraints (e.g., multidisciplinary nature, lack of resources, expertise, and time) often limit regular testing and prescription of individualised training. To the best of our knowledge, only three studies have utilised 3MT to prescribe HIIT, with beneficial improvements found (Vanhatalo, Doust and Burnley, 2008a; Clark et al., 2013; Courtright et al., 2016). Courtright et al. (2016) utilised 3MT to prescribe HIIT in

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

competitive swimmers and found significantly improved CS (3.3%), despite the low volume of HIIT prescribed (900-3000 yards.week⁻¹; 40-60 min.week⁻¹). However, all three studies only explored this methodology for 4 weeks, which is not dissimilar to a typical taper period, and therefore a reduction in training volume and increase in intensity could have naturally led to the observed improvements (Hellard et al., 2017). Therefore, studies monitoring long-term responses to HIIT prescribed on the basis of the CS concept and 3MT are required to confirm the usefulness of this concept in the design of personalised HIIT in swimming.

To extend the utility of the CS concept, Dekerle et al. (2002) postulated critical stroke rate (CSR) as a biomechanical surrogate of the CS, which represents the highest stroke rate (SR) a swimmer can maintain for an extended period of time. Dekerle et al. (2002) and Franken et al. (2013) also demonstrated that there is a link between CSR and CS, as the recruited swimmers spontaneously adopted SR similar to CSR when asked to swim at CS. Apart from representing a physiological boundary, Barden and Kell (2009) and Franken et al. (2013) suggested that CS also represents a biomechanical threshold beyond which stroke mechanics become compromised, thus suggesting this concept for technical training. Indeed, Dekerle et al. (2002) suggested constructing training with the aim to swim at CS with the $SR < CSR$, consequently requiring swimmers to adopt and maintain longer stroke length (SL) either through application of greater force or the improved efficiency with which the force is applied. Swimming coaches have previously suggested that lower volume, higher intensity focused programmes could be detrimental to technical development, as technique is optimally practiced at low intensities (Nugent, Comyns and Warrington, 2017). Whilst acknowledging the need for learning technical skills at low intensity, questions have been raised as to how completing high volumes at low intensity optimises technique adopted by swimmers in races, given that stroke behaviour differs as speed increases and fatigue develops (Chollet, Chabies and Chatard, 2000; Barbosa et al., 2008). The CS and CSR concepts therefore seem theoretically appealing to provide both physiological and technical stimuli closely replicating the demands of racing, however the impact of this strategy on technical development in competitive swimmers has not been investigated to date.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

Therefore, the aim of the present study was to utilise the CS and CSR concepts to prescribe individualised HIIT to a squad of highly-trained swimmers for 3 days.week⁻¹ over 15 weeks (one season). The purpose of this study was to monitor the physiological, technical, and performance changes when these concepts were applied over an extended period of time, and with a reduced training volume (≤ 30 km.week⁻¹).

5.3 Methods

5.3.1 Participants

A performance squad of 16 swimmers was recruited in the present study, which had received approval from the Research Ethics Approval Committee for Health at the University of Bath. One swimmer withdrew from the study and three swimmers were excluded from the study due to lack of compliancy with the designed training and/or testing procedures. The remaining 12 swimmers with characteristics described in **Table 5.1** were utilised for data analysis. All participants were competitive swimmers that regularly competed in regional, national and/or international events and completed a training volume of ~ 40 -45 km.week⁻¹ (8-9 swim sessions and 2-3 land sessions.week⁻¹). Within the recruited squad, there were five swimmers that specialised in freestyle, two in butterfly, one in breaststroke, three in backstroke and one in individual medley. The participants had no known history of respiratory, cardiovascular, metabolic or musculoskeletal disease and were not taking any medications that might have affected the variables under investigation. Prior to any testing all participants and parents were informed of the protocol, risks and potential discomfort associated with the procedures and potential benefits, both verbally and in writing, and gave their written informed consent.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

Table 5.1. General and performance characteristics of the recruited competitive swimmers.

Subject	Sex	Age (y)	Height (cm)	Weight (kg)	Tr.age (y)	1 st and 2 nd main event	1 st Main event PB (% WR)*
S1	F	17	163	53	8	200 m; 100 m freestyle	90%
S2	F	17	180	77	7	100 m; 200 m freestyle	85%
S3	F	16	187	66	6	400 m; 800 m freestyle	90%
S4	M	16	180	67	8	200 m; 100 m freestyle	79%
S5	M	16	180	70	6	200 m; 100 m freestyle	81%
S6	M	15	184	71	7	100 m; 200 m butterfly	82%
S7	F	15	165	57	8	100 m; 200 m butterfly	81%
S8	M	17	191	74	7	400 m; 200 m individual medley	85%
S9	M	15	178	59	5	100 m; 200 m breaststroke	82%
S10	F	15	177	65	7	200 m, 100 m backstroke	86%
S11	M	17	182	73	10	100 m; 200 m backstroke	83%
S12	M	14	180	59	6	200 m, 100 m backstroke	78%
Mean		16	179	66	7		84%
SD ±		1	8	8	1		4%

*Current world record (WR) for a short course (25 m) pool in the given event. Tr.age, training history; PB, personal best.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.3.2 Experimental design

The present study took place in a short-course season (September-December), and started 2 weeks after the swimmers had returned to training from a 1-2 weeks off-season break in order to reduce the impact of a break on the magnitude of improvement in the present study (Zacca et al., 2019b). In total, the testing protocol consisted of eight visits to the swimming pool over a 15-week period, and three HIIT intervention blocks that were prescribed using the CS and CSR concepts. The duration of the intervention was 4 weeks for the first and second intervention blocks, and 2 weeks for the final (third) block. The duration of the last block was reduced to allow an appropriate taper prior to a key national competition. One week prior to the first HIIT intervention block, the swimmers completed a 3MT and 200 m test at CS on separate days. These tests were performed to determine CS, D' and stroke parameters which were subsequently utilised to prescribe individualised HIIT for each swimmer. As the subjects in this study previously performed 3MT, the subjects were not asked to complete a familiarisation trial for this test. However, all swimmers completed a familiarisation trial with the 200 m test at CS. Considering that 4 weeks of HIIT is a sufficient period to recognise physiological improvements with previously trained athletes (Courtright et al., 2016; Clark et al., 2013; Vanhatalo, Doust and Burnley, 2008a), the 3MT and 200 m test at CS were conducted in the subsequent week to a training intervention block to re-prescribe HIIT for the following intervention block, and to establish the impact of the intervention on the investigated parameters. During this week, training intensity and volume were reduced in order to optimise results from the tests (see the "Training volume reduction and monitoring" section below). Both tests were preceded by a 5-min warm up at low intensity to minimise the impact of prior exercise on D', and were followed by 5-min rest (Jones et al., 2010; Vanhatalo and Jones, 2009). All trials were completed in a 50 m pool using a push-off start, conventional turns, and occurred at the same time of the day (± 1 h) (Drust et al., 2005). The subjects completed the tests and intervention in their main stroke. One swimmer specialising in individual medley completed tests and intervention in freestyle. No modifications in the swimmers' hydration, dietary, or sleeping habits were made in the present study, however the swimmers were always encouraged to come to the HIIT sessions hydrated, eaten sufficiently and rested as typically emphasised by the coaching staff working with the recruited squad. Strong verbal

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

encouragement was provided throughout the tests and training intervention, and time and distance were recorded to the nearest hundredth of a second and cm, respectively. In testing, subjects were not informed of their performance to prevent pacing (in 3MT) and deliberate change in stroking technique (in 200 m test at CS). In addition to the prescribed HIIT intervention, the swimmers engaged in their normal strength and conditioning programme (2-3 sessions.week⁻¹), low intensity and skill-based swimming sessions (3-4 sessions.week⁻¹), as well as speed development (repetitions of ≤ 100 m) sessions (1 session.week⁻¹), which were not modified in the present study.

5.3.3 Three-min all-out test

The test started with one minute of standing rest before a subject was given a 10 s warning prior to a push-off start. Subjects were asked to swim at an ‘all out’ swimming speed from the beginning of the test i.e. “as fast as you possible can at any given time during the test” and “leave nothing in reserve for the rest of 3MT”. Swimming time splits were recorded using a handheld stopwatch (Finis Inc., 3 x 100 m, California, USA) at every 10 m as the swimmer’s head was visualised passing the cone. Ten meters stages were marked with fluorescent cones placed parallel to the swimmer’s lane at every 5 m along the pool deck to enable the calculation of split times as well as displacement (D) of the swimmer at 150 s and 180 s. A 10 s countdown was given to the researcher that walked with a cone alongside a swimmer and placed a cone at 150 s and 180 s at the furthest point reached (i.e., a hand). Distance at 150 s (D₁₅₀) and 180 s (D₁₈₀) were recorded using a 50-meter tape measure placed parallel to the swimming lane and were used for the calculation of CS and D’ using the following equations (Courtright et al., 2016):

Equation 5.1

$$CS = (D_{180} - D_{150})/30$$

Equation 5.2

$$D' = [(D_{150}/150) - CS] \times 150$$

Based on our experience utilising 3MT in practice, in the situation when a swimmer did not complete a turn in the last 30 s of the test, which would lead to underestimation of CS utilised in training where turns are regularly performed (i.e., compromised ecological validity), CS was calculated as the average speed in the last 50 m of the test

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

to account for the potential impact of turn on speed. A visual inspection of each swimmer's speed-time 3MT profile was conducted to identify any occurrence of pacing, and the subjects that paced were asked to repeat the 3MT again on a different day. A peak speed (i.e., the speed measured in the first 25 m) and average speed for the first 150 s ($\text{speed}_{150\text{s}}$) and 180 s ($\text{speed}_{180\text{s}}$) were also derived from 3MT.

5.3.4 200 m test at CS

The swimmers were asked to swim at CS for 200 m. Pace was controlled with a Finis Tempo Trainer (Finis Inc., California, USA) that was preprogrammed to the CS pace required to swim each 50 m. The swimmers were instructed to be at each 50 m marker (i.e., the wall) on the bleep of the tempo trainer to ensure that the predetermined CS pace was followed throughout the test. To keep speed as constant as possible (i.e., to minimise effect of turns and underwater swimming on speed), and be consistent between tests and training intervention, swimmers were instructed to perform two underwater dolphin kicks off each wall (except for the breaststroker, who completed a single pull-out as they would do in a race). The stroke parameters and speed were measured in the last three 50 m laps as the first 50 m lap was utilised to allow swimmers to settle into the CS pace. As previous studies demonstrated that swimmers spontaneously adopt SR values close to CSR when asked to swim at CS (Dekerle et al., 2002; Franken et al., 2013), the SR associated with the closest 50 m time to CS pace was used for identification of the CSR estimate (SR@CS) and stroke count (SC@CS). In most swimmers this corresponded to the 3rd or 4th 50 m lap, where swimmers were within $0.90 \pm 0.77\%$ (0.36 ± 0.30 s) of the required CS time which is within the acceptable difference between actual and required time utilised in previous studies (i.e., $\pm 2.5\%$) (Franken et al., 2013; Seifert et al., 2007). The SR was measured with a handheld stopwatch (Finis Inc., 3 x 100 m, California, USA) from three consecutive stroke cycles in the middle section of each lap (i.e., 20-30 m) by an experienced coach. To standardise the SR procedure, the SR was obtained from a right-hand entry for freestyle and backstroke, when an initial side movement of hands after stroke extension took place for breaststroke, and from the first entry of hands into the water for butterfly. The speed derived from the 50 m time closest to CS pace was also utilised to calculate SL@CS and SI@CS as indicators of swimmers' propelling efficiency using the following formulas (Smith, Norris and Hogg, 2002):

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

Equation 5.3

$$SL@CS = \text{speed} / SR@CS$$

Equation 5.4

$$SI@CS = \text{speed} \times SL@CS$$

5.3.5 Training intervention

The established CS, D' and CSR estimates were utilised to design swimmers' individualised HIIT programme. Following the HIIT study design utilised previously by Clark et al. (2013) and Courtright et al. (2016), HIIT based on fractional depletion of D' was prescribed twice a week. A 'HIIT efficiency session' utilising a combination of CS and CSR concepts was prescribed once a week. To enable the majority of swimmers to recover and perform maximally in subsequent HIIT, HIIT sessions were separated by a minimum of ~35 h, in which swimmers trained at low intensity or had complete rest. In HIIT based on fractional depletion of D', 60% and 80% D' depletion schemes (% D') were used to determine the target interval time for specific distances using the following formula (Courtright et al., 2016; Pettitt, 2016):

Equation 5.5

$$\text{Interval time} = [\text{distance} - (D' \times \% D')]/CS$$

These HIIT sessions consisted of 5 x 60% D' or 3 x 80% D' intervals. Each interval time was calculated to accumulate a duration of ~3 min in 60% D' scheme and ~3.5 min in 80% D' as this time interval has been shown to favour gains in CS and $\dot{V}O_{2MAX}$ (Pettitt, 2016; Bacon et al., 2013) and to evoke $\dot{V}O_{2PEAK}$ consistently (Dicks et al., 2017). These target interval durations meant that swimmers swam repetitions of 200-250 m in 60% D' format and 250-300 m in 80% D' format. This HIIT was prescribed with a work-to-rest ratio of 1:1 for 60% D' and 1:1.5 for 80% D', as suggested by Pettitt (2016).

In the HIIT efficiency sessions, the swimmers were instructed to complete 10 repetitions of ~2.5 min duration at CS with ~30 s rest (5:1 work-to-rest ratio; ~30 min in total), which has been previously shown to elicit stable blood lactate, $\dot{V}O_2$ and heart rate responses as well as to reduce level of technical impairment as exercise at this

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

intensity continues (Nikitakis et al., 2019; Oliveira et al., 2012; Dekerle et al., 2010). To meet this interval duration, the swimmers specialising in freestyle/backstroke and breaststroke/butterfly were prescribed with repetitions of 200 m and 150 m, respectively. As suggested by Dekerle (2006), in order to elicit and stabilise positive changes in technique (i.e., greater SL, SI), whilst swimming at CS, the swimmers were also instructed to reduce and maintain their SR below established SR@CS by 2 cycles.min⁻¹ (~5-6%) (i.e., ‘double task constraint’ strategy) (Alberty et al., 2011). This SR was imposed by a metronome (Tempo Trainer, Finis, California, USA) placed under the swimmer’s cap. Throughout these sessions, the coach was providing technical feedback and instructions to swimmers as to how to adopt and maintain higher SL.

Prior to each main HIIT set, swimmers completed a ~20 min warm up that consisted of low-intensity swimming, technical (drill) swimming and was supplemented with a short ‘priming’ HIIT set performed above CS. To optimise and control for the effect of warm up on subsequent performance in the designed HIIT main set, and to ensure swimmers depleted similar proportion of their D’, the HIIT warm up set (4-5 x 100 m interspersed with ~15 s rest) was designed to accumulate ~6 min in the severe exercise intensity domain depleting 60% of D’, and was followed by ~15-20 min of passive recovery. This priming protocol strategy has been shown to optimise the balance between maintaining faster $\dot{V}O_2$ kinetics and allowing complete or near-complete restoration of muscle energetic reserves and homeostasis (D’), thereby facilitating performance in the subsequent severe-intensity exercise, and the accumulation of time spent above 90% of $\dot{V}O_{2MAX}$ ($T@\dot{V}O_{2MAX}$) (Bailey et al., 2009; Ferguson et al., 2010; Buchheit and Laursen, 2013). Throughout the intervention period, the head coach was given a pre-programmed prescription sheet that was designed to personalise HIIT sets and warm up prior to HIIT for each swimmer.

5.3.6 Training volume reduction and monitoring

The head coach was instructed to keep total swimming volume ≤ 30 km.week⁻¹ (minimum 25% reduction versus previous training practice) at all times throughout the intervention. In order to achieve this the following modifications were made: one low-intensity session was removed (~4.5 km); the three HIIT sessions prescribed in the present study with total volume of ~2.7 km (80% D’), ~3.8 km (60% D’); ~3.5 km (the

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

HIIT efficiency session) allowed for a reduction of volume by ~4 km; the remaining three low-intensity sessions were reduced from ~5.5 km to ~4.5 km (~3 km reduction); and the session with the focus on speed development was reduced from ~5 km to ~3.5 km (~1.5 km reduction). The total volume was further reduced by incorporating a ‘testing week’ after each intervention block. In this week, one low intensity session was removed (~4.5 km), and the two remaining low intensity sessions were utilised for 3MT (1.5 km) and 200 m test at CS (1.5 km), allowing a further reduction in volume by ~6 km. The coach was also instructed to reduce the 80% D’ HIIT set by 1 repetition, 60% D’ set by 2 repetitions and HIIT efficiency set by 5 repetitions, reducing volume further by ~1.8 km. As the ‘testing weeks’ also coincided with the weeks where competitions took place, and full prescription of HIIT was not a priority due to testing, the coach made the decision as to which swimmers completed reduced version of HIIT or swam the designed HIIT sessions at low intensity. Throughout the study, volume of training in kilometres (km), number of swimming sessions, and distribution of the volume performed at low intensity (<CS) and at high intensity (\geq CS) in individual swimmers were monitored on a daily basis.

5.3.7 Performance monitoring

As the swimmers regularly competed throughout the intervention period, progression in personal best (PB) times in swimmers’ main events was also monitored. Personal best times for the swimmers’ 1st and 2nd main events were investigated. The 1st and 2nd main events were considered the events that represented the highest and 2nd highest number of FINA points, respectively. The PB times for the 1st and 2nd main events completed in both short course and long course seasons were checked from a publicly available online resource containing all PB times for the swimmers (<https://www.swimmingresults.org/individualbest/>). As the intervention took place in the short course season, we converted current long course PB times to short course times utilising a time conversion tool (<http://www.pullbuoy.co.uk/times>). If the short-course PB time was faster compared to the converted long-course PB time, the short-course PB was utilised. However, if the converted long-course PB time was faster compared to the current short-course PB, the converted long-course PB time was utilised to capture performance improvement elicited by the long-course season (January-August) that preceded our intervention. The fastest time for the given event was subsequently utilised as the swimmer’s current PB. This procedure was adopted

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

in order to avoid overestimation of the performance change elicited in the intervention, as the intervention was preceded by a long course season, meaning that some PBs achieved in the previous short course season were ~7-8 months old at the start of the intervention, and therefore in some cases could misrepresent swimmers' PB performance level, that was likely to have improved. To capture performance changes corresponding to the individual testing time points, performance for 200 m was predicted utilising the following equation (Pettitt, 2016):

Equation 5.6

$$\text{Predicted 200 m time} = (\text{distance} - D') / \text{CS}$$

5.3.8 Statistical analyses

The investigated variables were log transformed before analysis to reduce non-uniformity of error and to express effects as percent changes (Hopkins, 2002b). Effects were adjusted for sex by including a binary covariate in the model. Magnitude-based inferences were used to provide an interpretation of the real-world relevance of the outcomes (Batterham and Hopkins, 2006). The smallest worthwhile change (SWC) in performance-related variables (CS, D', peak speed, speed_{150s}, speed_{180s}, 200 m predicted time, PB times for 1st and 2nd main event) was $0.3 \times$ coefficient of variation (CV) (Hopkins, Hawley and Burke, 1999). The CV values were obtained from a previous reliability study in the same population (for CS, D', peak speed, speed_{150s}, speed_{180s}) (Piatrikova et al., 2018), or from published literature in similar populations (for race performance measures) (Stewart and Hopkins, 2000; Mitchell et al., 2018a). For technique-related parameters (SL@CS, SI@CS, SR@CS, SC@CS), the SWC was defined as a small standardised effect based on Cohen's effect size principle ($0.2 \times$ between-athlete SD) (Cohen, 1988). The size of the percentage change was also interpreted by using thresholds for moderate ($0.9 \times$ CV), large ($1.6 \times$ CV), very large ($2.5 \times$ CV) and extremely large effects ($4 \times$ CV) (Hopkins, Hawley and Burke, 1999). Threshold values for effect size statistics were >0.2 (small), >0.6 (moderate), >1.2 (large), >2.0 (very large), and >4.0 (extremely large). An effect was deemed '*unclear*' if the chance that the true value was beneficial was $>25\%$, with odds of benefit relative to odds of harm (odds ratio) of <66 . Otherwise, the effect was deemed clear, and was qualified with a probabilistic term using the following scale: $<0.5\%$, *most unlikely*; $0.5-5\%$, *very unlikely*; $5-25\%$, *unlikely*; $25-75\%$, *possible*; $75-95\%$, *likely*; $95-99.5\%$,

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

very likely; >99.5%, *most likely* (Hopkins, 2007). For succinctness in the figures, symbols were utilised to illustrate beneficial (✓), harmful (✗) and trivial (↔) effects. The number of symbols indicate the likelihood for the differences to be substantial, with one symbol referring to *possible*, two to *likely*, three to *very likely* and four to *most likely* substantial effects. The changes in the investigated variables are displayed as means \pm 90% confidence limits (CL).

5.4 Results

5.4.1 Training characteristics

The average total volume and intensity distribution for individual weeks in the investigated 15-week period is displayed in the **Figure 5.1**. Average total volume swam by swimmers per week was 20.80 ± 6.52 km, with 15.69 ± 5.39 km (75.31 ± 9.25 % of total volume) undertaken below CS and 5.11 ± 2.24 km (24.69 ± 9.25 % of total volume) undertaken at or above CS. On average, swimmers completed 7 ± 1 swimming sessions.week⁻¹. Compliancy to the planned HIIT sessions was 80 ± 12 % (24 ± 4 completed sessions of 30 planned sessions). Approximately ~6% of the planned sessions were not completed due to short-term injury or illness (e.g., URTI, injury outside of training), ~6% due to commitments outside of swimming training (e.g., school or work activities), ~4% due to short-term changes in training plan prior to competitions, and ~3% were not completed due to training cancellation as a result of adverse weather.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

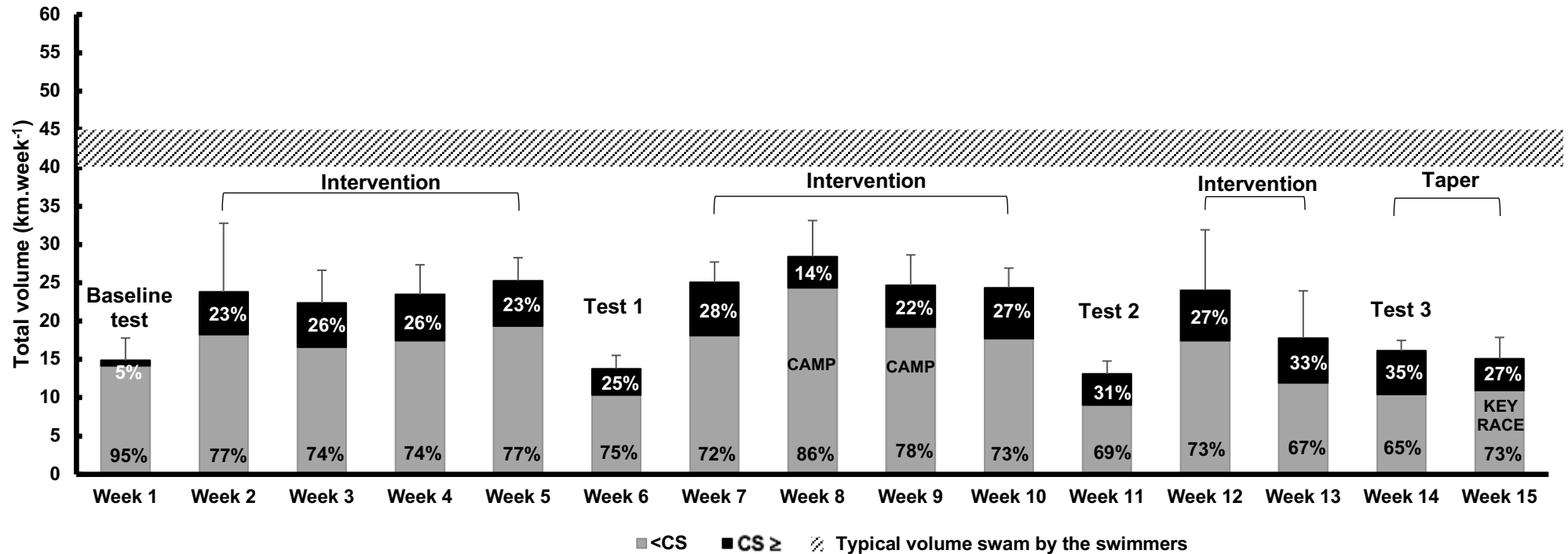


Figure 5.1. Average total volume and intensity distribution during a 15-week intervention period. The error bars represent standard deviations.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.4.2 Physiological and performance parameters

Mean speed-time 3MT profiles for baseline and tests 1-3 are illustrated in the **Figure 5.2**. Mean \pm SD values, mean \pm 90% CL percentage changes, and individual percentage changes for the investigated physiological and performance parameters are illustrated in the **Figure 5.3** and **Figure 5.4**.

5.4.2.1 Critical speed

In relation to SWC for CS ($\pm 0.3\%$) there was a *most likely* beneficial increase in CS from baseline to test 1 ($4.29 \pm 1.88\%$) and test 3 ($5.44 \pm 1.56\%$) and a *very likely* beneficial increase in CS from baseline to test 2 ($4.32 \pm 2.63\%$), all representing extremely large effects ($>3.6\%$). The changes between tests 1-2 ($0.004 \pm 2.92\%$) and tests 2-3 ($1.09 \pm 1.94\%$) were *unclear*.

5.4.2.2 D'

In relation to SWC for D' ($\pm 2.7\%$) there was a *very likely* harmful decrease in D' from baseline to test 1 ($-25.83 \pm 15.57\%$) and test 2 ($-21.42 \pm 16.30\%$) and a *most likely* harmful decrease in D' from baseline to test 3 ($-25.24 \pm 7.46\%$). The magnitude of this change was very large for tests 1 and 3 ($>22.75\%$) and large for test 2 ($>14.56\%$). The change in D' between tests 1-2 was *unclear* ($6.25 \pm 24.89\%$), however, there was a *possibly* harmful decrease in D' between tests 2-3 ($-6.43 \pm 18.24\%$), representing a small effect.

5.4.2.3 Speed_{150s} and Speed_{180s}

In relation to SWC for speed_{150s} and speed_{180s} ($\pm 0.18\%$) there was a *most likely* beneficial increase in both variables from baseline to test 1 ($2.08 \pm 0.84\%$; $2.60 \pm 1.09\%$), test 2 ($1.87 \pm 0.91\%$; $2.48 \pm 1.16\%$) and test 3 ($2.49 \pm 0.88\%$; $2.96 \pm 0.87\%$), respectively. The change in speed_{150s} between baseline and both test 1 and 2 represented very large effect ($>1.5\%$) and extremely large effect between baseline and test 3 ($>2.4\%$). The change in speed_{180s} between baseline and tests 1-3 represented extremely large effects ($>2.4\%$). The changes for speed_{150s} and speed_{180s} between tests 1-2 ($-0.13 \pm 1.27\%$; $-0.11 \pm 1.52\%$) and tests 2-3 ($0.39 \pm 0.83\%$; $0.31 \pm 0.96\%$) were *unclear*, respectively.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.4.2.4 Peak speed

In relation to SWC for peak speed ($\pm 0.4\%$) there was a *likely* harmful decrease in peak speed from baseline to test 1 ($-0.89 \pm 1.17\%$), representing a small effect ($>0.4\%$) and a *possibly* harmful decrease from baseline to test 2 ($-0.74 \pm 1.53\%$), representing a small effect ($>0.4\%$). The changes in peak speed between baseline-test 3 ($0.08 \pm 1.67\%$), tests 1-2 ($0.35 \pm 1.38\%$) and tests 2-3 ($0.12 \pm 0.69\%$) were *unclear*.

5.4.2.5 Predicted 200 m performance

In relation to SWC for predicted 200 m time ($\pm 0.4\%$) there was a *most likely* beneficial reduction in 200 m time from baseline to test 1 ($-2.07 \pm 0.86\%$) and test 3 ($-2.65 \pm 0.96\%$) and a *very likely* beneficial decrease from baseline to test 2 ($-2.08 \pm 1.01\%$). The change in 200 m time from baseline to test 1 and test 2 represented moderate effects ($>1.26\%$), and large effect from baseline to test 3 ($>2.24\%$). The changes in the 200 m time between tests 1-2 ($-0.06 \pm 1.29\%$) and tests 2-3 ($-0.40 \pm 0.86\%$) were *unclear*.

5.4.2.6 Competition performance

In relation to SWC for competition performance ($\pm 0.4\%$), there was a *likely* beneficial decrease in PB time for the swimmers' 1st main event ($-1.15 \pm 1.30\%$) and a *very likely* beneficial decrease in PB time for the swimmers' 2nd main event ($-1.57 \pm 0.85\%$). The change in PB time for the 1st main event and 2nd main event represented a small effect ($>0.4\%$) and moderate effect ($>1.26\%$), respectively.

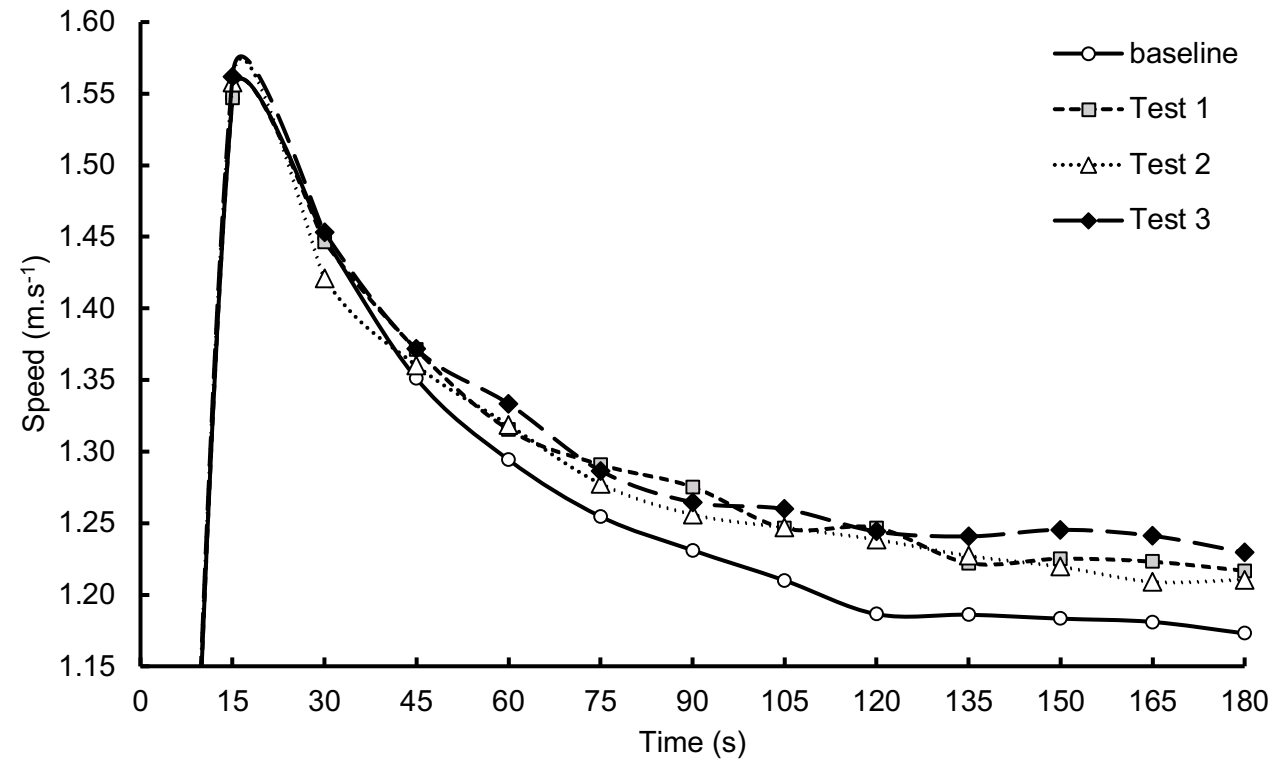


Figure 5.2. Mean speed-time profiles for the 3-min all-out tests for baseline and tests 1-3.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

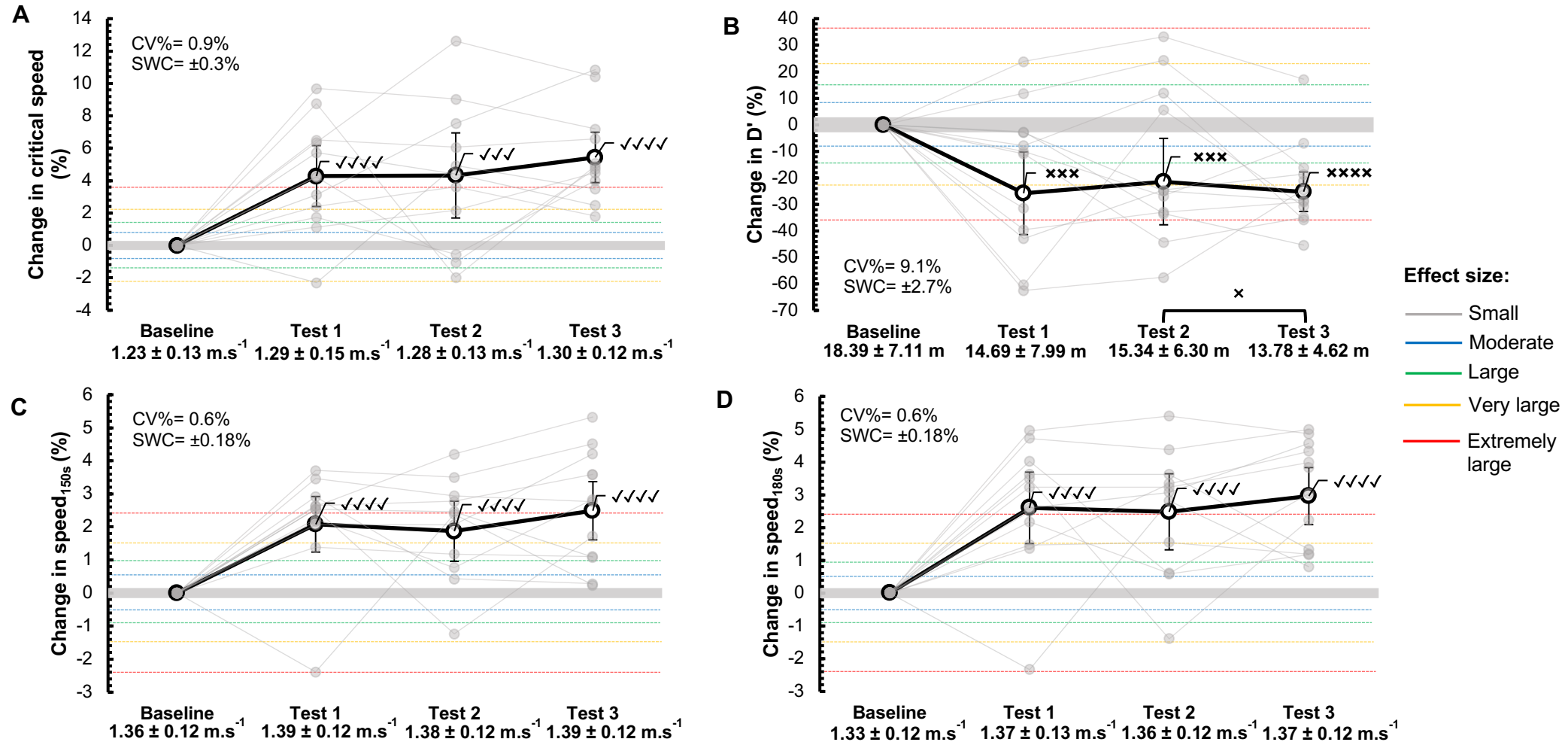


Figure 5.3. Changes in critical speed (A), D' (B), speed_{150s} (C) and speed_{180s} (D) from baseline to tests 1-3. Data are presented as means \pm 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects.

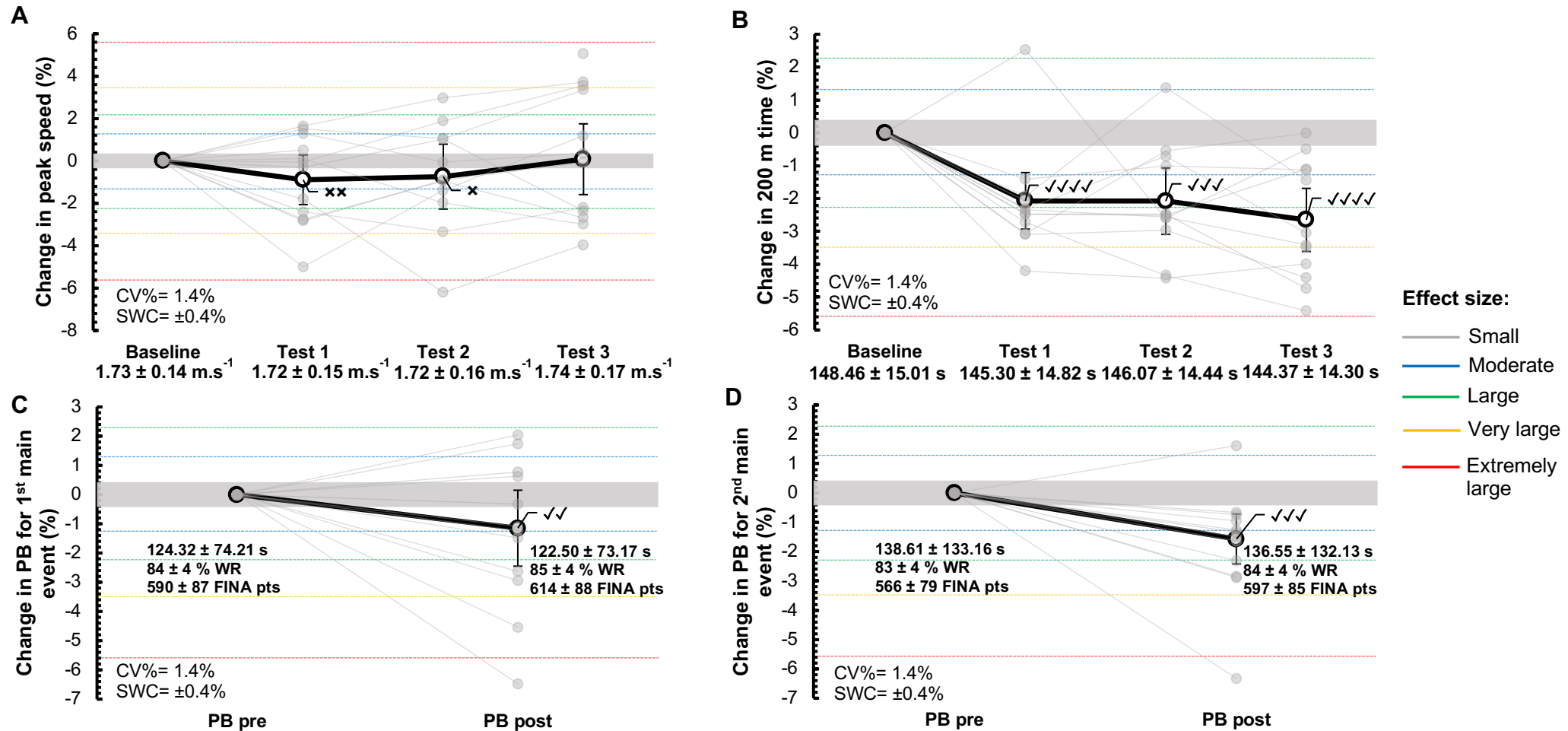


Figure 5.4. Changes in peak speed (A) and predicted 200 m time (B) from baseline to tests 1-3, and in PBs for 1st (C) and 2nd main event (D). Data are presented as means \pm 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.4.3 Technical parameters

5.4.3.1 Stroke length

In relation to standardised SWC for SL@CS (± 0.2), there was a *likely* trivial decrease in SL@CS from baseline to test 1 (-0.05 ± 0.20), a *likely* trivial increase from baseline to test 2 (0.04 ± 0.26), and a *very likely* trivial decrease from baseline to test 3 (-0.05 ± 0.13). There was also *likely* trivial increase in SL@CS between tests 1-2 (0.09 ± 0.14) and *likely* trivial decrease between tests 2-3 (-0.12 ± 0.15) (**Figure 5.5**).

5.4.3.2 Stroke index

In relation to standardised SWC for SI@CS (± 0.2), there was a *possibly* beneficial increase from baseline to test 1 (0.16 ± 0.12) and test 2 (0.16 ± 0.18). There was a *likely* trivial increase in SI@CS between baseline and test 3 (0.14 ± 0.11). There was also *most likely* trivial increase in SI@CS between tests 1-2 (0.02 ± 0.09) and *most likely* trivial decrease between tests 2-3 (-0.05 ± 0.07) (**Figure 5.5**).

5.4.3.3 Stroke rate

In relation to standardised SWC for SR@CS (± 0.2), there was a *likely* beneficial increase in SR@CS from baseline to test 1 (0.47 ± 0.36 ; small effect) and a *very likely* beneficial increase from baseline to test 3 (0.43 ± 0.20 ; small effect). The change in SR@CS from baseline to test 2 was *unclear* (0.21 ± 0.48). There was a *possibly* harmful decrease in SR@CS from test 1 to test 2 (-0.22 ± 0.36 ; small effect) and a *possibly* beneficial increase from test 2 to test 3 (0.25 ± 0.32 ; small effect) (**Figure 5.5**).

5.4.3.4 Stroke count

In relation to standardised SWC for SC@CS (± 0.2), there was a *likely* trivial increase in SC@CS from baseline to test 1 (0.02 ± 0.19), a *likely* trivial decrease from baseline to test 2 (-0.08 ± 0.23), and a *very likely* trivial increase from baseline to test 3 (0.03 ± 0.12). There was also *likely* trivial decrease in SC@CS between tests 1-2 (-0.08 ± 0.16) and *likely* trivial increase between tests 2-3 (0.12 ± 0.14) (**Figure 5.5**).

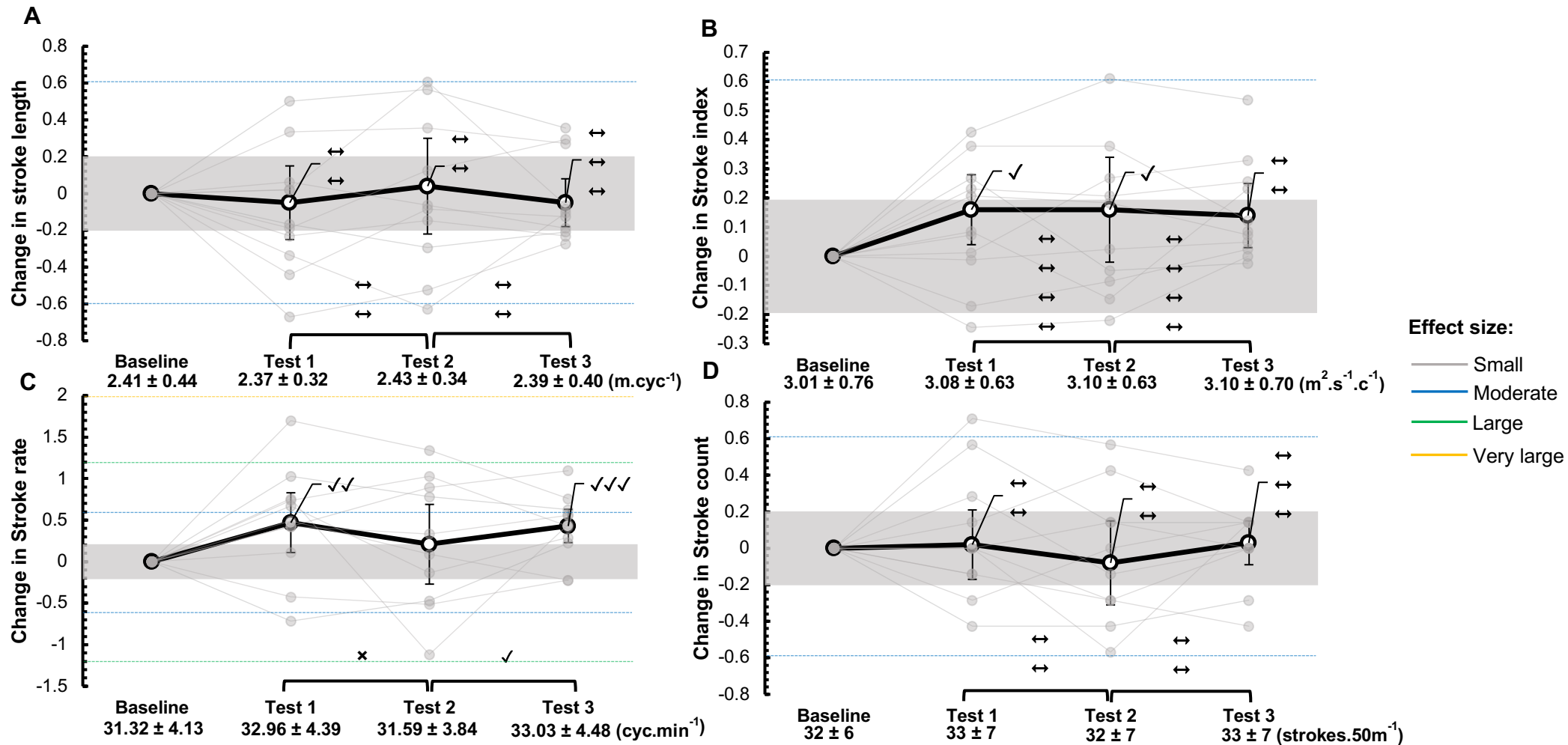


Figure 5.5. Changes in stroke length (A), stroke index (B), stroke rate (C) and stroke count (D) adopted at critical speed from baseline to tests 1-3. Data are presented as means \pm 90% CL (black lines) alongside individual responses (light grey lines). Grey shaded area represents trivial effects.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.5 Discussion

The principal finding of the present study is that HIIT prescribed on the basis of the CS and CSR concepts was associated with beneficial changes in several aspects of swimming performance, despite the swimmers completing substantially reduced training volume during one short-course season. Specifically, the format of the training prescribed in the present study promoted beneficial increases in CS, speed_{150s}, speed_{180s}, SR@CS and SI@CS. Despite a decrease in D' and peak speed, the changes were not sufficient to have a negative impact on modelled 200 m performance and actual competitive performance in the swimmers' two best events PB times, as all effects were clear and beneficial in relation to SWC. Changes in SL@CS and SC@CS were trivial, suggesting that the swimmers were able to hold similar SL and SC despite swimming at higher CS. To our knowledge, this is the first study: 1) to implement the CS concept and 3MT for personalised HIIT for an extended period (>4 weeks); 2) to implement a combination of CS and CSR concepts for training prescription; 3) to explore how longer-term HIIT effects the parameters related to swimmers' technical ability at CS (i.e., SR, SL, SI, SC).

5.5.1 Critical speed

Overall, in relation to baseline measurement, a 5.4% (+0.07 m.s⁻¹) improvement in CS was observed in the investigated short-course season. The greatest proportion of this improvement was observed after the first training block (test 1: 4.3%; +0.05 m.s⁻¹), after which changes in CS stabilised between test 1-2, before increasing again by 1.1% (+0.02 m.s⁻¹) from test 2 to 3. The magnitude of improvement in CS over the first 4-week HIIT intervention period is higher compared to Courtright et al. (2016), which is the only study to date to utilise 3MT in the prescription of HIIT in swimming. Specifically, utilising 5x60, 4x70 and 3x80% D' depletion schemes, Courtright et al. (2016) prescribed HIIT for 4 weeks (2 days.week⁻¹) to 17 competitive freestyle swimmers and observed an increase of 3.3% (+0.04 m.s⁻¹) in CS. The potential explanation for the greater CS increase in the present study could be related to the actual design of the HIIT. Whilst Courtright et al. (2016) assigned interval durations of ~1 min 40 s with fixed distance (150 yards=137.16 m) to 11 swimmers and ~2 min 50 s (250 yards=228.6 m) to 6 swimmers, in the present study, interval repetition distance was adjusted to allow each swimmer to accumulate durations of ~3 min and

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

~3.5 min in 60% D' and 80% D', respectively. Previous studies examining the optimal duration of HIIT intervals for CS and $\dot{V}O_{2MAX}$ improvement have suggested interval durations of 3-5 min to account for the time required to achieve $\dot{V}O_{2MAX}$, to evoke $\dot{V}O_{2PEAK}$ consistently (Pettitt, 2016; Dicks et al., 2017) and to accumulate sufficient $T@ \dot{V}O_{2MAX}$ (Buchheit and Laursen, 2013). We had no access to $\dot{V}O_2$ measurements in the present study to demonstrate $T@ \dot{V}O_{2MAX}$, however, considering that previous studies have demonstrated that 60 and 80% D' schemes of 3-5 min intervals evoke $\dot{V}O_{2PEAK}$ consistently (Dicks et al., 2017; Pettitt et al., 2015), the intervention designed in the present study potentially allowed the recruited swimmers to accumulate more $T@ \dot{V}O_{2MAX}$ compared to the swimmers recruited by Courtright et al. (2016). Specifically, considering that the time constant to achieve $\dot{V}O_2$ values near $\dot{V}O_{2MAX}$ is ~15-20 s when swimming at intensities 95-105 % $\dot{V}O_{2MAX}$ (Sousa, Vilas-Boas, Fernandes, 2014; Sousa et al., 2015a), which is similar to the intensity the swimmers swim at in the HIIT intervals designed in the present study (i.e., 97-103% of maximal speed achieved in the incremental step test), it would take ~1 min to achieve values near $\dot{V}O_{2MAX}$ in the first HIIT interval. Therefore, the swimmers in the study of Courtright et al. (2016) would have accumulated ~40 s and ~1 min 50 s near $\dot{V}O_{2MAX}$ in the first short (150 yards) and long interval (250 yards), respectively. Assuming similar speed of $\dot{V}O_2$ on-kinetics between groups, the swimmers in the present study would accumulate more $T@ \dot{V}O_{2MAX}$ in the first 3 min (~2 min) and 3.5 min (~2.5 min) interval, as well as more overall $T@ \dot{V}O_{2MAX}$ due to the longer interval durations. Additionally, the swimmers in the present study were prescribed with a shorter rest interval in relation to work interval (work-to-rest ratio: 1:1 in 60% D', 1:1.5 in 80% D') compared to Courtright et al. (2016) (1:3 in 150 yard and 1: 1.8 in 250 yard), and completed a HIIT warm-up set 15-20 min prior to the main HIIT set. These differences could have allowed the swimmers in the current study to start from a higher $\dot{V}O_2$ baseline and with faster $\dot{V}O_2$ on-kinetics, allowing them to accumulate greater total $T@ \dot{V}O_{2MAX}$ (Buchheit and Laursen, 2013; Bailey et al., 2009), which has been previously suggested as key for evoking central and peripheral adaptations.

The observed increase in CS is also greater compared to the studies of Faude et al. (2008) and Nugent et al. (2019), which investigated the effect of 4 and 7 weeks of low volume, higher intensity training (20 and 17 km.week⁻¹) in a similar population. These

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

authors observed a 0.7% ($+0.01 \text{ m}\cdot\text{s}^{-1}$) increase in individual anaerobic threshold (IAT) and a 1.5% ($-0.02 \text{ m}\cdot\text{s}^{-1}$) decrease in speed at a fixed blood lactate value of $4 \text{ mmol}\cdot\text{L}^{-1}$ ($\text{speed}_{4\text{MMOL}}$), respectively. The differences in the findings could be related to the design of HIIT. Specifically, these studies utilised percentages of IAT and/or racing times to prescribe HIIT intervals, which were also mostly prescribed over shorter distances of 15-100 m. Considering that shorter intervals might not allow as great $T@V\dot{O}_{2\text{MAX}}$ as longer intervals (Sousa et al., 2017; 2018; Buchheit and Laursen, 2013) and the fact that CS concept might allow for more accurate prescription of HIIT compared to prescriptions based on IAT or racing times only, this could account for the observed differences.

In relation to the seasonal improvement, the observed magnitude of increase in CS is also greater compared to a number of studies that have explored changes in CS derived from a traditional protocol (Machado et al., 2011; national swimmers; 2.8%) (Santhiago et al., 2009; national and international swimmers; males: 4.3%; females: 3.8%) (Toubekis et al., 2011; regional male and female swimmers; 2.4%) or modified 3MT-12 x 25 m test (Mitchell et al., 2019; national and international swimmers, $+0.04 \text{ m}\cdot\text{s}^{-1}$) and in $\text{speed}_{4\text{MMOL}}$ (Costa et al., 2012; national male swimmers; 1.5%) (Anderson et al., 2006; elite international swimmers; males: $\sim 1.5\%$; females: $\sim 2.2\%$) over an extended period of time (12-26 weeks). Consequently, the present HIIT format was associated with greater seasonal CS improvement, which has also been achieved through a substantially lower training volume compared to those prescribed in the aforementioned studies ($40\text{-}60 \text{ km}\cdot\text{week}^{-1}$).

5.5.2 D', $\text{speed}_{150\text{s}}$ and peak speed

An increase in CS was accompanied by a substantial reduction in D' (-4.7 m ; -25%) in the investigated intervention period. The greatest proportion of this decrease occurred after the first intervention block (-3.9 m ; -26%), after which D' remained substantially below baseline values despite small fluctuations of $\pm 6\%$ between remaining tests. The observed impact of HIIT on D' is consistent with the findings of previous studies, which utilised a similar HIIT. Prescribing HIIT based on fractional D' depletion, Courtright et al. (2016) and Clark et al. (2013) observed 16% (-3.5 m) and 11% (-24 m) decreases in D' of competitive swimmers and soccer players, respectively. This is, however, in contrast to studies of Vanhatalo, Doust and Burnley

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

(2008a), Poole, Ward and Whipp (1990) and Gaesser and Wilson (1988), who observed no clear changes in W' despite significant increases in CP after 4, 7 and 6 weeks of HIIT, respectively.

The greater magnitude of D' decrease in the present study could be related to the design of longer HIIT intervals, which may have increased CS at the expense of D' (Pettitt, 2016). Clark et al. (2013) suggested that in order to increase D' , intervals with duration of less than 2 min performed at intensity exceeding 130% $\dot{V}O_{2\text{MAX}}$ (extreme domain) should be applied to allow for a greater contribution of D' to the interval bout. Based on the recent findings of Courtright et al. (2016), it appears that swimming intervals with durations of ~1 min 45 s are still insufficient to increase D' , therefore intervals with durations of less than 90 s are likely to be required. Indeed, supramaximal sprint interval training has been previously shown to increase D'/W' . Jenkins and Quigley (1993) observed a 50% increase in W' following 8 weeks of supramaximal HIIT (5 x 60 s maximal cycling bouts, 3 days.week⁻¹) in moderately-trained population. Similarly, Santhiago et al. (2009) observed ~14% increase in D' after 7 weeks of intensified training which involved the implementation of a HIIT series with distances ≤ 100 m (~60 s) performed at race-pace velocities and above in a training programme of national and international swimmers. This potentially confirms the suggestion of Clark et al. (2013) and could explain the greater drop in D' in the present study as the contribution of D' to the designed intervals was lower compared to the majority of aforementioned studies (4-5% vs 12-24%). Additionally, the decline in D' could have been accentuated further by the implementation of HIIT sessions swam at CS (Dekerle, 2006). Indeed, Jenkins and Quigley (1992) observed a 30% increase in CP accompanied by a 26% decrease in W' following 8 weeks of endurance training prescribed at CP (30-40 min at CP, 3 days.week⁻¹).

It is important to note that based on available evidence, it is currently inconclusive as to what strategies should be utilised in order to improve D' , and what impact a measured increase in D' might have on actual swimming performance, as multiple factors seem to influence this parameter (e.g., nutrition, fatigue, prior exercise, the protocols utilised to establish D'). Indeed, Johnson et al. (2011) warned that W' lacks sensitivity to be utilised for monitoring high-intensity performance independent of other measures, and therefore suggested to use more reliable measures related to W'

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

such as power/speed_{150s}. A *most likely* beneficial increase of 2.5% (+0.04 m.s⁻¹) was observed in speed_{150s} in the present intervention, with the greatest increase occurring after the first training block (2.1%; +0.03 m.s⁻¹), which is in agreement with Courtright et al. (2016). However, similarly to D', peak speed (an indicator of maximal anaerobic power), a measure previously related to D' (Mitchell et al., 2014) and maximal accumulated oxygen deficit (Kalva-Filho et al., 2017), declined after the first training block (-0.9%; -0.01 m.s⁻¹) and remained below baseline values after the second training block (-0.7%; -0.01 m.s⁻¹) before it returned to the values similar to baseline values at the end of the intervention (+0.1%; 0.004 m.s⁻¹). This is somewhat in contrast with Mitchell et al. (2019), who reported that national and international swimmers had a tendency to have faster peak speed and greater D' towards the end of season compared to the early part of the season (+0.03 m.s⁻¹; + 2 m, respectively). Therefore, it can be concluded that whilst increases in CS were observed in the present intervention this was at the expense of D' and temporarily peak speed, which declined over the investigated season.

5.5.3 Technique

The present intervention was associated with a beneficial increase in SR@CS and SI@CS whilst changes in SL@CS and SC@CS exhibited only trivial changes. Specifically, with the exception of *unclear* SR@CS changes observed in test 2, SR@CS increased from baseline to test 1 by 7.0 ± 5.6 % and to test 3 by 6.4 ± 3.0 %. The SI@CS increased from baseline to test 1 by 4.9 ± 4.0 % and changed only trivially for rest of the intervention (test 2: 4.9 ± 5.7 %; test 3: 4.2 ± 3.6 %). To our knowledge, no previous studies have assessed the impact of HIIT on technical parameters adopted when swimming at CS, and so direct comparisons are difficult to draw. However, several studies have investigated the effect of HIIT programmes on technical parameters when swimming maximal TT (Nugent et al., 2019; Faude et al., 2008; Termin and Pendergast, 2000). With the exception of SL, our findings are in contrast with those of Nugent et al. (2019) and Faude et al. (2008), who observed no change in SR, SL and SI adopted by swimmers in 50 m and 400 m freestyle TT after 7 weeks and in 100, 400 m TT and 100 m at submaximal speed after 4 weeks of HIIT, respectively. The contrasting findings could be attributed to differences in the intensity utilised to evaluate technical changes, or alternatively to the format of HIIT employed. As postulated earlier, the present HIIT format could have potentially allowed for more

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

precise prescription and a greater proportion of time spent near maximal $\dot{V}O_2$, therefore the swimmers spent more time adopting and optimising stroke mechanics at intensities close to race-pace. It is important to mention that both authors also simultaneously investigated the effect of higher volume, lower intensity strategies on the same technical parameters, and observed compromised SI and SL values in 50 m freestyle TT (Nugent et al., 2019) and 100 m TT (Faude et al., 2008). This is in contrast with the recommendations made by coaches who suggest these strategies to optimise technical proficiency (Nugent, Comyns and Warrington, 2017). Indeed, accumulating evidence suggests that intensity rather than volume plays a key role in eliciting changes in performance parameters of highly-trained swimmers including those related to technique. Termin and Pendergast (2000) who utilised SR-speed relationship to prescribe low volume, high intensity programme to national swimmers over 4 years, observed a yearly shift in this relationship so the recruited swimmers were able to swim with greater SL and with lower energy cost at a range of velocities ($1\text{--}2\text{ m}\cdot\text{s}^{-1}$) as well as demonstrated greater maximal SR values. Termin and Pendergast (2000) attributed these changes to the prescription of more specific physiological and technical stimuli mirroring what is required from swimmers in races (i.e., maintaining technical proficiency whilst being under severe metabolic stress). Similarly, Costa et al. (2013) recently attributed 3.6% and 3.7% greater increase in SL and SI adopted by swimmers in 200 m freestyle events to ~30% greater proportion of the volume swam at higher intensities in comparison to the previous season.

When comparing the present findings to studies that have examined typical seasonal changes in technical parameters at fixed submaximal intensity, our findings are somewhat in agreement with Anderson et al. (2006) and Costa et al. (2012) who examined technical changes at fixed blood lactate concentration of $4\text{ mmol}\cdot\text{L}^{-1}$ within a season. Whilst Costa et al. (2012) observed non-significant changes in $SR_{4\text{MMOL}}$ and $SL_{4\text{MMOL}}$, increases in $speed_{4\text{MMOL}}$ (1.5%) and $SL_{4\text{MMOL}}$ (2.3%) resulted in significantly increased $SI_{4\text{MMOL}}$ (3.7%) in the investigated season. Anderson et al. (2006) did not provide results for $SI_{4\text{MMOL}}$, however, did observe a 2-4% increase in $SR_{4\text{MMOL}}$, which was accompanied by a corresponding decrease in $SL_{4\text{MMOL}}$. In contrast to Anderson et al. (2006), we observed only trivial changes in $SL_{@CS}$. Given the findings of the studies that postulated that intensity might play an important role in mediating changes in technical parameters (Costa et al., 2013; Termin and Pendergast, 2000), the current

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

HIIT format could have attenuated decreases in SL@CS, despite the ~5% increase in CS. Specifically, in all HIIT sessions but especially in the sessions swam at CS with fixed and lower SR than SR@CS, swimmers swam at high intensities with the main emphasis on developing technical capabilities of swimming with greater SL despite being under substantial metabolic stress. This therefore required consistent application of greater force and/or improved ability to apply the same force more efficiently over longer period. Consequently, developing this ability in training could have allowed swimmers to maintain the initial SL@CS values despite swimming at greater CS in subsequent trials, also demonstrated through ~4-5% increase in SI@CS in the intervention period.

One of the limitations of the present study is that the change in technical parameters was not evaluated at a fixed speed (i.e., baseline CS) as typically done, as monitoring technical changes at fixed intensity (and thus similar metabolic demands) was the main objective in this study. Despite this limitation, interpretations can be drawn from the results of previous studies that investigated behaviour of SR, SL, SI when swimming at ± 2.5 -5% of CS or MLSS (Franken et al., 2013; Barden and Kell, 2009; Dekerle et al., 2005b; Pelarigo et al., 2016). Specifically, if the swimmers' technique was to be evaluated at baseline CS throughout the intervention, based on the observed increases in CS from baseline to tests 1-3, the swimmers would swim at ~95.7% of baseline CS in tests 1-2 and ~94.5% of baseline CS in test 3. Therefore, based on the aforementioned studies, it can be postulated that swimmers could be able to swim at this fixed speed with lower SR and greater SL and SI.

It is unclear whether the HIIT format employed in the present study would have beneficial effect on SL@CS if applied for a longer period of time or more frequently within the given time, considering the time highly-trained swimmers require to change technical behaviour. Indeed, from anecdotal coaching evidence, swimmers can take up to a year to effectively embed a new technical behaviour within a stroke, depending on a scale of technical change. Therefore, 14 weeks might have not been a sufficient period to observe beneficial changes in SL@CS. Utilising the 5-A model, which was proposed by Carson and Collins (2011) for refining and monitoring technical changes effectively, most of the swimmers in the current study were at the stages of "Adjustment" (i.e., correcting the flaws in technique) with some entering the

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

“Automation” stage (i.e., internalising the desired change) at the end of the intervention. Therefore, a longer intervention or greater frequency of HIIT efficiency sessions might be required to observe meaningful changes in SL@CS. Interestingly, the three swimmers identified by the coach as entering the “Automation” stage/improving technical proficiency actually improved their SL and SI beyond utilised SWC. Consequently, the present intervention was not associated with detrimental effects on technical parameters as previously suggested by coaches favouring higher volume, lower intensity programmes for technical development. Instead, the group of recruited swimmers maintained initially measured SL@CS values whilst swimming at higher CS (higher SI@CS) with higher SR@CS. Further research is required to elucidate what changes in technical parameters can be observed when this training format is applied for longer period (e.g., consecutive seasons) and what effects this strategy might have on the stroke mechanics adopted by swimmers in their main competitive events.

5.5.4 Competition and predicted performance

Despite the observed decreases in D' and temporarily peak speed, these changes were not sufficient to have a negative impact on the predicted 200 m performance, and more importantly, on swimmers' performance in actual competitions. Instead, the recruited swimmers improved their predicted 200 m time by 2.7% over the intervention period and the change in the PB times for 1st and 2nd main competitive events represented a decrease in time of 1.2% and 1.6%, respectively, allowing the swimmers to score ~30 extra FINA points and swim closer to WR by ~1.4%. This is in contrast with previous studies that employed low volume, high intensity strategies in similar populations and found smaller and non-significant performance changes (Nugent et al., 2019; Kilen et al., 2014; Faude et al., 2008). The authors of these studies attributed the findings to a limited potential for improvement in the highly-trained swimmers recruited, the short intervention duration, or prior experience in HIIT. The swimmers recruited in the present study had similar or higher performance levels compared to the swimmers recruited in the aforementioned studies and engaged in different formats of HIIT prior to the intervention. Therefore, the reduced capacity to improve and prior experience in HIIT did not limit performance improvements in the present study. However, it is important to note that the improvement in swimmers' PB for the 2nd event represented greater and clearer magnitude of improvement compared to the improvement in the

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

swimmers' PB for the 1st event. This is perhaps due to greater room for improvement in the swimmers' 2nd main event, as the initial PB times in the 2nd main event represented ~25 less FINA points and occurred ~1% lower in relation to WR time compared to the initial PB times in the 1st event. Implementing a somewhat similar training strategy to the present study, Termin and Pendergast (2000) utilised the SR-speed relationship to prescribe low volume, high intensity training over 4 years and observed ~2.3% yearly performance improvements in national swimmers specialising in 100 and 200 yard freestyle events. Therefore, the potential factors that could have contributed to positive performance changes in the present study could be attributed to the use of longer HIIT intervals, as discussed previously, and arguably to more precise prescription of HIIT taking into account combination of CS, CSR and D' as opposed to using percentages of IAT, race-pace velocities or maximal efforts to prescribe HIIT.

The observed improvement in PBs represents a somewhat greater magnitude compared to what is typically observed in elite international swimmers, who typically improve ~0.4-1% a year (Costa et al., 2010; Anderson et al., 2008; Pyne, Trewin and Hopkins, 2004; Mujika et al., 1995). However, in this case the greater improvement could be attributed to the performance level and age of the recruited swimmers, who despite being highly-trained and racing at national and/or international meets, did not represent elite international standard and were of younger age (~16 y). Comparing the magnitude of improvement with similarly aged and trained swimmers who compete in similar distances, the performance improvements observed in the present intervention are somewhat similar to typical yearly performance improvements previously observed by Costa et al. (2011) (i.e., ~1.8% in 100 m and 400 m events and ~1.3% in 200 m events in highly-trained swimmers aged 15-17). In addition to this, compared to the magnitude of performance improvement observed in the same swimmers and events in the season prior to the intervention (i.e., long-course season, January-July) (1st event: -1.0 ± 0.9 %; 2nd event: -0.7 ± 0.8 %), the magnitude of PB improvement achieved in the present study is similar to that achieved in the 1st event and ~2-fold greater in the 2nd main event. Consequently, despite being implemented for substantially shorter period of time (3.5 months) and with substantially lower volume, the present intervention was associated with; 1) similar improvements in PBs compared to those typically achieved by similarly-aged and trained swimmers in a

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

year; and 2) PB improvements similar (1st event) and greater (2nd event) compared to those observed in the season prior to the beginning of the intervention in the same cohort of swimmers.

There are multiple factors which could have contributed to the observed improvements in competition performance. Firstly, given the strong relationships that were previously observed between CS, speed_{4MMOL}, SR_{4MMOL} and SI_{4MMOL} and performance, the performance improvements may be partly attributed to improvements in CS as well as SR@CS and SI@CS (Mitchell et al., 2014; 2018b; Anderson et al., 2008; Costa et al., 2012; 2013). Mitchell et al. (2018b) observed strong relationships between CS and performance in 50, 100 and 200 m events, with this relationship appearing to be stronger for longer race distances (50 m, $R^2=0.29$, $p=0.03$; 100 m, $R^2=0.32$, $p=0.008$; 200 m, $R^2=0.61$, $p<0.001$). From a technical perspective, out of several measures derived from an incremental step test, Anderson et al. (2008) identified SR_{4MMOL} as the best predictor of competition performance in national and international swimmers ($r=0.41-0.46$), whilst Costa et al. (2012) suggested the use of SI_{4MMOL} as an indicator of performance variation in national swimmers. Considering the substantial role energetics and technique play in swimming performance, the improvements observed in the aforementioned parameters could have allowed for improvements in the swimmers' races in which energy is predominantly derived from the aerobic system (Hellard et al., 2018; Figueiredo et al., 2011) and in which swimmers strive to maintain technical efficiency (e.g., minimising decline in SL). Specifically, allowing swimmers to spend more time at intensities closer to those at which the swimmers raced could have allowed swimmers to facilitate and consolidate physiology, technique and psychology utilised in races. Indeed, Mujika et al. (1995) observed that improvement in elite swimmers' performance was strongly related ($r=0.69$; $p<0.01$) to the mean intensity of the training season but not to volume or frequency of training. This is in agreement with recent findings of Costa et al. (2013) and Pla et al. (2019) who attributed greater performance improvements to greater time spent at race-pace velocities in swimmers.

Alternatively, the substantial reduction in volume could have reduced training stress and facilitated recovery from the prescribed programme, allowing manifestation of prescribed training in performance when it came to competition. Elbe et al. (2016)

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

observed lower stress levels and better recovery levels in highly-trained swimmers who were completing lower volume, higher intensity training ($17 \text{ km}\cdot\text{week}^{-1}$) compared to swimmers completing high volume at lower intensities training ($35 \text{ km}\cdot\text{week}^{-1}$) over a 12 week period. Elbe et al. (2016) attributed this finding to the differences in the training content (i.e., less volume, more variation and more opportunities to rest). Indeed, it has been repeatedly discussed that training that encompasses large training volumes can result in accumulated (chronic) fatigue, which may not only compromise optimal performance in training and achievement of peak performance in competitions but also can lead to over-use injuries and burnout in swimmers (Nugent et al., 2017; Termin and Pendergast, 2000). Sein et al. (2010) investigated the relationship between swimming volume and shoulder pain and injury in elite swimmers and found that the swimmers who swam more than $35 \text{ km}\cdot\text{week}^{-1}$ were four times more likely to suffer from supraspinatus tendinopathy. Assuming that swimmers typically take ~ 35 strokes per 50 m and swim $\sim 40 \text{ km}\cdot\text{week}^{-1}$ for ~ 47 $\text{weeks}\cdot\text{year}^{-1}$ ($28\,000 \text{ strokes}\cdot\text{week}^{-1}$ or $1.3 \text{ million strokes}\cdot\text{year}^{-1}$), the present intervention allowed a reduction in shoulder revolutions by almost 50%, without compromising on swimmers' performance. Consequently, it is reasonable to speculate that the current intervention could have provided a stimulus better replicating the needs of competitive racing compared to those typically provided by higher volume lower intensity focused training programmes, as well as allowing enhanced recovery. The enhanced recovery may have been achieved through the combination of reducing stress (lower training volume), varying the type of stress applied (reduced training monotony) and taking a complete break from a stressful activity (reduction in 1 swim session $\cdot\text{week}^{-1}$, implementation of recovery weeks).

It is important to note that our findings apply mainly for competitive events of 100-400 m and therefore it is unclear whether the implemented strategy would be beneficial for the swimmers specialising in 50 m events, where energy derived from the anaerobic system is substantial ($\sim 70\text{-}90\%$) (Rodríguez and Mader, 2010; Capelli, Pendergast and Termin, 1998). Indeed, Mitchell et al. (2018b) found that CS explained less variation in 50 m performance ($R^2=0.29$, $p=0.03$) compared to peak speed ($R^2=0.56$; $p<0.001$) and D' ($R^2=0.37$; $p=0.01$). Therefore, as a decrease in D' and temporarily peak speed were observed in the present study, shorter and more intense HIIT intervals that allow greater contributions of D' to the total interval might be

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

needed to optimise training preparation of sprint swimmers (Clark et al., 2013). Indeed, Pettitt (2016) suggested that athletes seeking to improve aerobic capacity without compromising on sprinting capacity should use 90 s interval bouts which yield smaller improvements in CS with preservation of D' . In addition to this, Pettitt (2016) also suggested the implementation of a resistance training programme which has been shown to increase W' without compromising on CP. Alternatively, the concept of 'anaerobic' CS, where the slope of the distance-time relationship is calculated from time trials of 10-150 m, has been previously utilised to plan training sessions with the aim to activate anaerobic metabolism (Espada et al., 2016; Marinho et al., 2012; Neiva, Fernandes, Vilas-Boas, 2011), however, the impact of this strategy on performance in sprint events or D' has not been investigated to date.

Finally, it is important to point out that no further improvements in many of the investigated variables between tests 1-2 were observed despite a 4-week block being completed. This was originally unexpected, however, after further analysis of the completed training in the corresponding training block and the timing of testing this could be attributed to a 9-day training camp that was organised to culminate in a weekend competition i.e., 1 week prior to the test 2 schedule. Specifically, this camp was organised abroad and was accompanied by ~15% increase in total volume (from low intensity) in relation to the previous training week and ~30% increase in total volume in relation to the average volume swam in the previous 4 weeks (acute:chronic ratio: 1.3). In addition to this, 2 extra dry-land training sessions were completed, adding additional acute load to the swimmers. Considering that >10% week-to-week increases in training load and acute:chronic workload ratios exceeding 1.3 have been discouraged to avoid risk of overtraining and injury, the investigated swimmers were potentially exposed to too great a training overload during the camp (Gabbett, 2016). This, together with cancelation of 2-4 HIIT sessions (either as a result of poor weather conditions and/or due to short-term changes in programme to adjust for the planned competition) might subsequently have impacted on the results observed in test 2. Unfortunately, we had no control over the organisation of the camp except for the HIIT prescribed. However, after the swimmers' return to the normal programme prescribed prior to the camp, completing this programme for 2 weeks was associated with improvements greater or equal to SWC but *unclear* in several parameters when compared to test 2 (CS: $1.1 \pm 1.9\%$; speed_{150s}: $0.4 \pm 0.8\%$; speed_{180s}: $0.3 \pm 0.9\%$;

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

predicted 200 m time: $-0.4 \pm 0.9 \%$; SR@CS: $d = 0.3 \pm 0.3$). A 2-week training period was likely an insufficient time to observe clear changes in the investigated parameters between tests 2-3 and therefore testing after the taper (i.e. 2 weeks later) may have enabled us to see clearer beneficial improvements based on the aforementioned observed trends, and to measure variables when swimmers were tapered and in a peak condition. Unfortunately, due to logistical arrangements this was not possible.

5.6 Practical applications

The present study extended the utility of a swimming 3MT such that the derived parameters can be utilised not only to regularly monitor progression of swimmers, but to also prescribe individualised HIIT specific to swimmer's physiological and technical capacities in the given stroke. The ability to effectively prescribe individualised HIIT to a larger group of swimmers on a regular basis has been a long-lasting issue in swimming due to the demanding resources, time, and expertise associated with currently utilised procedures (e.g., step tests, MLSS test) as well as technological and multidisciplinary constraints associated with swimming testing. As a result, in applied practice, swimming HIIT has been typically prescribed utilising several affordable methods (e.g., beats below HR_{MAX} , race-pace velocities, holding best average, adding a number of seconds to current PB). These methods are typically used to prescribe training to a group of swimmers with a set number of repetitions of equal distances and equal turnaround time, despite swimmers having different aerobic capacities (CS) and capacity to work above CS (D'). Consequently, supposedly equal training will likely lead to different training stimuli (e.g., different intensity and $T@VO_{2MAX}$) being prescribed to swimmers. The investigated method in the present study considers both the aerobic capacity (CS), and capacity to work above CS (D') of an individual swimmer in HIIT design, allowing swimmers to complete similar work and recovery time, and an equal number of repetitions, regardless of stroke specialty or level of athletes. This subsequently allows for improved individualisation and standardisation of HIIT training. Additionally, HIIT depletion schemes and HIIT efficiency sets allow swimmers to develop and practice stroke mechanics closer to those adopted in races whilst being under substantial metabolic stress, consequently, allowing for prescription of both physiological and technical stimuli specific to racing demands.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

The testing and training approach prescribed in the present study can be applied relatively easily by practitioners as it requires feasible resources, time and expertise. The prescribed HIIT times and SR can be imposed by utilising affordable equipment, such as tempo trainers, which can be programmed with the required SR and time for each lap, allowing the coaches to observe technique and give more frequent feedback to swimmers instead of taking times after each repetition to a large number of swimmers. The feasible methodology utilised in the present study can also allow coaches and applied sport scientists to account for the fact that swimmers usually have a main and form stroke whilst swimmers specialising in individual medley need to work on all four strokes to optimise progression in this event. To regularly obtain individual data for 2-4 strokes currently requires demanding procedures, whilst the 3MT performed in multiple strokes can be completed in a short time. Additionally, a freely available statistical analysis tool utilised in the present study (Hopkins, 2017) can be used by practitioners to assess meaningful changes in swimmer's performance in response to designed training, which is currently rare to see in swimming.

Finally, this study shows that volumes prescribed below 30 km.week⁻¹ for a short-course season did not limit positive changes in several performance aspects of highly-trained swimmers and in multiple cases exceeded those found by previous research studies investigating training strategies in swimming. Whilst allowing for positive performance changes, this strategy may also reduce the risk of overuse injuries, early specialisation, and burnout or drop-out from this sport, which were previously associated with the high-volume demands that traditional swimming training can pose on swimmers. Alternatively, the present study might also provide a useful strategy for coaches striving to deliver effective sessions despite limited pool time. Further research examining the application and the effects of the investigated approaches on performance, physiological and/or technical parameters for consecutive seasons and in different levels of swimmers would be useful to confirm the utility of this training strategy across a wider spectrum of swimmers (e.g., youth and elite) and coaches. Finally, the omission of a control group represents a limitation to this study and therefore, future research should investigate the discussed approaches alongside other approaches traditionally utilised by swimming coaches.

Chapter 5: Individualising training in swimming: evidence for utilising the critical speed and critical stroke rate concepts

5.7 Conclusion

In conclusion, the present study demonstrated that HIIT training prescribed on the basis of CS and CSR concepts for 3 days.week⁻¹ for one short-course season was associated with meaningful beneficial changes in several physiological, technical, and performance parameters in highly-trained swimmers who completed a substantially reduced volume of training. The feasible approach associated with testing and application of these concepts in training represents a promising start for the improved prescription and monitoring of swimming training, whilst also potentially reducing the risk of overuse injuries, burnout or early specialisation in swimmers.

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

Chapter 6: Monitoring heart rate variability responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

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6.1 Abstract

Purpose: Firstly, to examine whether heart rate variability (HRV) responses can be modelled effectively via the Banister Impulse-Response model (IR) when the session rating of perceived exertion (sRPE) alone, and in combination with subjective wellness measures, are utilised. Secondly, to describe seasonal HRV responses and their associations with changes in critical speed (CS) in competitive swimmers. **Methods:** Ten highly-trained swimmers collected daily 1-min HRV recordings, sRPE training load, and wellness scores via a HRV4Training application for 15-weeks. The IR model was used to describe chronic Root Mean Square of the Successive Differences (rMSSD) responses to training, with sRPE and subjective wellness measures used as systems inputs. CS was obtained from a 3-min all-out test conducted at the beginning and end of the monitored period. **Results:** A high level of agreement between predicted and actual HRV data ($R^2=0.66 \pm 0.25$) was observed when sRPE alone was used. Model fits improved in the range of 4-21% when different subjective wellness measures were combined with sRPE, representing *trivial-to-moderate* improvements. There were no significant differences in weekly group Ln rMSSD_{MEAN} ($p=0.34$) or weekly HRV coefficient of variation (Ln rMSSD_{CV}) ($p=0.12$), however, *small-to-large* effect size changes ($d=0.21-1.46$) were observed in these parameters throughout the season. Large correlations were observed between seasonal changes in both HRV measures and CS (Δ Ln rMSSD_{MEAN}: $r=0.51$, $p=0.13$; Δ Ln rMSSD_{CV}: $r=-0.68$, $p=0.03$). **Conclusion:** The IR model and data collected via a novel smartphone application can be used to model HRV responses to swimming training and non-training related stressors. Large relationships between seasonal changes in measured HRV parameters and CS provide further evidence for incorporating a HRV-guided training approach to optimise adaptations in individual athletes.

Key words: heart rate variability, modelling, monitoring, training, swimming

6.2 Introduction

The overarching aim of coaches and sport practitioners is to design training programmes that are effective (i.e., elicit desirable adaptations) and sustainable (i.e., minimise the risk of injury, non-functional overreaching or overtraining), with the ultimate goal being to allow athletes to achieve maximal performance when it matters the most. Our understanding of effectively managing training programmes of athletes has advanced (Plews et al., 2013a; Buchheit, 2014; Borresen and Lambert, 2009), but sports practitioners and athletes still face the ever-lasting challenge of effectively monitoring, prescribing and balancing the training stimulus and recovery whilst often operating under the constraints of limited resources and time.

A promising method to monitor athletes' adaptations to prescribed training involves the regular monitoring of the cardiac autonomic nervous system (ANS), specifically its parasympathetic arm via the measurement of resting heart rate variability (HRV) and its day-to-day variation (Flatt and Esco, 2016). Indeed, HRV has been shown to be related to training load (Flatt, Hornikel and Esco, 2017; Garet et al., 2004; Chalencon et al., 2012; 2015), performance (Chalencon et al., 2012; Garet et al., 2004), health (Williams et al., 2017; Hellard et al., 2011) and psychological status of athletes (Flatt, Esco and Nakamura, 2018; Flatt, Hornikel and Esco, 2017) in various sports including swimming. Consequently, HRV has become a promising candidate for monitoring global responses of athletes to training in various sports (Chalencon et al., 2012; Williams et al., 2017).

Given this, Chalencon et al. (2012) explored the possibility of applying the Banister Impulse-Response (IR) model (Banister et al., 1975) to describe the impact of training on nocturnal HRV measures in ten competitive swimmers over a 30-week period. The modelled HRV responses were compared with performance responses, which is the traditional outcome parameter in this model, but the requirement for regular performance testing has limited its applicability in applied practice. Chalencon et al. (2012) not only showed remarkable model fit to both HRV ($R^2=0.79\pm0.07$) and performance responses ($R^2=0.84\pm0.14$), but also observed very large positive correlations between the behaviour of HRV and performance in response to training load. The authors consequently suggested that HRV measurements may be used as a proxy to track the impact of the training load on athletes' fatigue and adaptation status

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

without interfering with athletes' training programmes to collect performance measures. However, considering the methodology utilised by Chalencon et al. (2012), some potential issues can be raised regarding the accuracy and practical applicability of the methods. In terms of the accuracy, the authors collected HRV only once per week and utilised the high-frequency (HF) component of HRV rather than collecting and averaging daily HRV measurements of the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (rMSSD), which has been recommended and is a commonly used method in sports performance (Buchheit, 2014; Plews et al., 2013a). In terms of the practicality, the need to purchase heart rate monitors, to collect and analyse nocturnal HRV data, and to calculate training load for each athlete based on the methods suggested by the authors (see Chalencon et al., 2012, appendix 2) would be challenging for regular swimming teams that typically have a large number of swimmers and limited resources, time and/or expertise to implement these procedures effectively. In addition to this, whilst nocturnal HRV measurements utilised by Chalencon et al. (2012) may theoretically provide better HRV recordings due to the reduced impact of environmental factors during sleep (Buchheit, 2014; Chalencon et al., 2015), there is also some evidence that nocturnal measures do not capture the impact of psychological stress on HRV as well as morning measures, and therefore may not capture this important aspect of athlete's status (Hynynen et al., 2011).

Given the recent development of affordable and easy-to-utilise smartphone technology, which is capable of obtaining valid HRV measures in ~1 min without a need for heart rate straps (Plews et al., 2017), and its built-in capacity to record various measures of training load and subjective wellness scores, the collection of daily HRV recordings without compromising on validity and practicality is now more feasible. Therefore, the primary aim of the present study was to examine whether the findings of Chalencon et al. (2012) could be replicated when daily morning 1-min recordings of rMSSD HRV measure collected via a novel smartphone application and the session rating of perceived exertion (sRPE) as a training load measure (i.e., a method utilised by most coaches) are utilised in the IR model as outputs and inputs, respectively. In addition to this, given that non-training related stressors can impact on athlete's responses to training (Flatt, Esco and Nakamura, 2018), measures of several subjective indicators of recovery status will be combined with sRPE as the systems inputs in

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

order to examine whether the ability to model HRV responses improves. Finally, as there is a lack of studies that have obtained daily measures of HRV in response to longer training periods (i.e., a season), an additional aim of the present study was to monitor HRV responses (i.e., weekly mean and coefficient of variation) and their associations with seasonal changes in critical speed, as a performance-related measure, in a group of highly-trained swimmers who were monitored over one short-course season.

6.3 Methods

6.3.1 Participants

A group of sixteen healthy and highly-trained swimmers from the same swimming team volunteered to participate in the present study. Ethical approval was received from the Research Ethics Approval Committee for Health at the University of Bath, and the study was conducted in accordance with the Declaration of Helsinki. Six swimmers were excluded from the data analysis either due to poor compliance with the procedures or withdrawal from the swimming programme. Ten swimmers with the general and performance characteristics described in **Table 6.1** were included in the final analyses. All participants and parents were informed of the risk and benefits associated with the study's procedures verbally and in writing and were asked to sign an informed consent before participating in the study.

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

Table 6.1. General and performance characteristics of the swimmers.

Subject	Sex	Age (y)	Height (cm)	Weight (kg)	Train. age (y)	1 st and 2 nd main event	1 st Main event PB (% WR)*
S1	M	15	184	71	7	100 m; 200 m butterfly	82%
S2	F	15	177	65	7	200 m, 100 m backstroke	86%
S3	F	17	180	77	7	100 m; 200 m freestyle	85%
S4	M	14	180	59	6	200 m, 100 m backstroke	78%
S5	M	16	180	70	6	200 m; 100 m freestyle	81%
S6	F	15	165	57	8	100 m; 200 m butterfly	81%
S7	M	16	180	67	8	200 m; 100 m freestyle	79%
S8	M	17	182	73	10	100 m; 200 m backstroke	83%
S9	M	15	178	59	5	100 m; 200 m breaststroke	82%
S10	F	17	163	53	8	200 m; 100 m freestyle	90%
Mean		16	177	65	7		83%
SD ±		1	7	8	1		4%

*Current world record (WR) for a short course (25 m) pool in the given event. Train.age, training history; PB, personal best.

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

6.3.2 Experimental design

The present study is an extension of the previous research study (i.e., Chapter 5), which examined physiological, performance and technical changes in response to a 15-week training programme. Briefly, swimmers were prescribed with individualised high-intensity interval training (HIIT) (3 times a week) based on the critical speed and critical stroke rate (CSR) concepts (i.e., 60% D' depletion scheme: 5 x 3 min intervals; 80% D' depletion scheme: 3 x 3.5 min intervals; efficiency HIIT: 10 x 150 m or 200 m at CS with 2 cycles.min⁻¹ lower stroke rate than CSR), whilst overall training volume was reduced ($\geq 25\%$). The study period represented a short-course swimming season (i.e., September-December) and included periods of overload, recovery, an overseas training camp (~1400 km travel by flight, 1 h time-zone loss), and taper, which also led into a key race of the season. In addition to the 3-min all-out tests (3MT) completed at the beginning of the study (week 1) and subsequently at the end of each training cycle (i.e., week 6, 11 and 14), the swimmers were also asked to collect daily HRV, training load and subjective wellness measures via a smartphone application that were subsequently utilised for the following purpose: 1) to monitor week-to-week HRV responses of the swimmers to the designed 15-week training programme; 2) to examine relationships between changes (Δ) in HRV and CS measures elicited over the season (from week 1 to week 14); and 3) to model HRV responses to training load alone, or in combination with subjective wellness measures, using the IR model (Banister et al., 1975). Prior to the study, all swimmers attended a meeting in which all procedures utilised to optimally collect HRV, training load and subjective wellness measures were explained and demonstrated. Subsequently, all swimmers were asked to collect the required data for a week in order to familiarise themselves with the required procedures. Any training advice given by the application based on collected measurements was hidden from the athletes and coach in the present study.

6.3.3 Heart rate variability

Swimmers were instructed to perform a 1-min HRV self-measurement each morning upon waking in a supine position whilst in a dark room and breathing spontaneously. Photoplethysmography (PPG) was utilised to acquire HRV readings via a commercially available smartphone application (HRV4Training). This method has

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

been shown to provide a valid measurement of HRV when compared to heart rate chest strap and electrocardiogram (ECG) procedures (Plews et al., 2017). All swimmers were instructed to collect a signal marked by the application as ‘optimal’. The rMSSD component of HRV was used for the analysis in the present study due to its reliability and practicality compared to other HRV indices (Al Haddad et al., 2011; Plews et al., 2013a). To examine HRV responses observed throughout the study, the rMSSD data were first log-transformed (Ln) to reduce non-uniformity of error and weekly (7 days) averages of Ln rMSSD (Ln rMSSD_{MEAN}) as well as its coefficient of variation (Ln rMSSD_{CV} = [Ln rMSSD_{SD}/Ln rMSSD_{MEAN}] x 100) were calculated for individual weeks and athletes. A 42-day exponentially weighted average of raw rMSSD (rMSSD_{42-EXP}) was calculated using Equation 6.1 and was utilised in the IR model as a representative marker of chronic training adaptation (Williams et al., 2018). The raw rMSSD values rather than Ln rMSSD values were used in this part of analysis, as raw rMSSD data allowed for better model fit to measured data. The rMSSD_{42-EXP} calculation was initiated with the mean rMSSD value observed across the first seven days of the monitoring period.

Equation 6.1

$$rMMSD\ EWMA_{today} = rMMSD_{today} \times \lambda_{\alpha} + ((1 - \lambda_{\alpha}) \times rMMSD\ EWMA_{yesterday})$$
$$where\ \lambda_{\alpha} = \frac{2}{42 + 1}$$

6.3.4 Training load

Upon completion of HRV measurement, the swimmers were asked to report their training load for the preceding day within the HRV4Training application. Specifically, the athletes were asked to provide an intensity score (Borg CR-10 scale) and duration (minutes) of their previous day’s training sessions, which were subsequently multiplied to calculate a daily sRPE score in arbitrary units (A.U.) (Foster et al., 2001). This approach was chosen as sRPE has been shown to be a valid method for estimating exercise intensity across multiple modes of exercise which was the case in the present study (pool and land training) (Herman et al., 2006; Wallace et al., 2008), and is also temporally robust up to 24 h post-exercise (Christen et al., 2016).

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

6.3.5 Subjective wellness scores

The psychometrics were recorded daily and immediately following HRV recordings via the HRV4Training application. The swimmers were asked to honestly and subjectively rate their sleep quality, lifestyle stress, motivation, mental energy, fatigue and muscle soreness on a sliding scale which was assigned with a 1-100 score by the application. For sleep quality, motivation and mental energy the scores closer to 100 represented positive scores whilst for lifestyle stress, fatigue and muscle soreness the scores closer to 100 represented negative scores.

6.3.6 The Banister Impulse-Response model

The mathematical relationship between training loads (system input) and $rMSSD_{42-EXP}$ (system output) was modelled for each athlete via the two-component IR model (Banister et al., 1975). This model is characterized by two gain terms (k_1 and k_2) and two time constants (τ_1 and τ_2) for the positive (adaptation) and negative (fatigue) component, respectively, and an initial performance level (p) which was represented by HRV:

Equation 6.2

$$\hat{p}^n = p^* + k_1 \sum_{i=1}^{n-1} w^i e^{-(n-i)/\tau_1} - k_2 \sum_{i=1}^{n-1} w^i e^{-(n-i)/\tau_2}$$

Additional terms were linearly added on to this model to incorporate subjective wellness measure data as an additional input (i.e., each predictor had a fitness and fatigue component that were finally added at the end). The model parameters were determined by minimising the Sum of Squares Error (SSE) between estimated and measured $rMSSD_{42-EXP}$ using the *dorem* package in R studio (RStudio, Inc., Boston, USA) designed by Jovanovic and Hemingway (2020) and a customised spreadsheet based on Clarke and Skiba (2013), which provides a step-by-step procedure for fitting the IR model using the Solver function in Excel.

6.3.7 Critical speed

To assess the relationships between change in the HRV parameters and performance-related measures during the investigated period, a change in CS (ΔCS) established

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

from the 3MT completed by swimmers in week 1 and week 14 was calculated. CS was chosen as it represents both a valuable performance and physiological variable (Poole et al., 2016).

6.3.8 Statistical analyses

The data are presented as means, standard deviations (SD) and 95% confidence limits (CL). To evaluate changes in $\text{Ln rMSSD}_{\text{MEAN}}$ and $\text{Ln rMSSD}_{\text{CV}}$ throughout the monitored period, one-way repeated measures ANOVA and effect size statistics were utilised. Standardised differences in mean values were calculated using thresholds described by Hopkins et al. (2009), where 0-0.2 was *trivial*, 0.2-0.6 was *small*, 0.6-1.2 was *moderate*, 1.2-2.0 was *large*, 2.0-4.0 was *very large*, and >4.0 was *extremely large*. A bivariate Pearson correlation was utilised to assess relationships between $\Delta \text{Ln rMSSD}_{\text{MEAN}}$ and $\Delta \text{Ln rMSSD}_{\text{CV}}$ and ΔCS from week 1 to 14. Default thresholds for correlations were 0.1, small; 0.3, moderate; 0.5, large; 0.7, very large; 0.9, nearly perfect (Hopkins, 2002a). To assess differences between the IR model fit (R^2) to actual $\text{rMSSD}_{42\text{-EXP}}$ data when sRPE was combined with different subjective scores as opposed to sRPE only, standardised differences and paired samples t-tests or the Wilcoxon signed-rank test were used. The Wilcoxon signed-rank test was performed on data showing non-normality. Statistical significance was set at $p < 0.05$.

6.4 Results

6.4.1 Weekly HRV responses

The changes in average weekly $\text{Ln rMSSD}_{\text{MEAN}}$ and $\text{Ln rMSSD}_{\text{CV}}$ along with average weekly sum of sRPE are illustrated in **Figure 6.1**. There were no statistically significant differences between weekly $\text{Ln rMSSD}_{\text{MEAN}}$ ($F_{(4.85, 43.64)}=1.17$, $p=0.34$). *Small* standardised differences were observed in weeks 7 ($d=0.21$) when compared to baseline (week 1) and in-between weeks 5-6 ($d=0.23$) and weeks 8-9 ($d=-0.27$). Similarly, there were no statistically significant differences between weekly $\text{Ln rMSSD}_{\text{CV}}$ ($F_{(5.29, 47.57)}=1.86$, $p=0.12$), however, *small-to-moderate* changes in $\text{Ln rMSSD}_{\text{CV}}$ were observed in week 4 ($d=-0.34$), week 5 ($d=-0.44$), week 6 ($d=-0.43$), week 7 ($d=-0.54$), week 9 ($d=0.23$), week 11 ($d=-0.39$), week 12 ($d=-0.66$), week 13 ($d=0.22$), week 14 ($d=-0.77$) and week 15 ($d=0.51$) when compared to baseline (week 1). In addition, *small-to-large* changes were observed in-between weeks 3-4 ($d=-$

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

0.59), weeks 7-8 ($d=0.70$), weeks 9-10 ($d=-0.36$), weeks 10-11 ($d=-0.35$), weeks 11-12 ($d=-0.36$), weeks 12-13 ($d=0.80$), weeks 13-14 ($d=-0.91$) and weeks 14-15 ($d=1.46$).

6.4.2 Correlation between seasonal changes in HRV measures and CS

Figure 6.2 illustrates correlations between $\Delta \text{Ln rMSSD}_{\text{MEAN}}$ vs ΔCS , and $\Delta \text{Ln rMSSD}_{\text{CV}}$ vs. ΔCS . There was a large but non-significant correlation between $\Delta \text{Ln rMSSD}_{\text{MEAN}}$ vs ΔCS ($r=0.51 \pm 0.44$; $p=0.13$), whilst the correlation between $\Delta \text{Ln rMSSD}_{\text{CV}}$ and ΔCS was large and significant ($r=-0.68 \pm 0.35$, $p=0.03$).

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

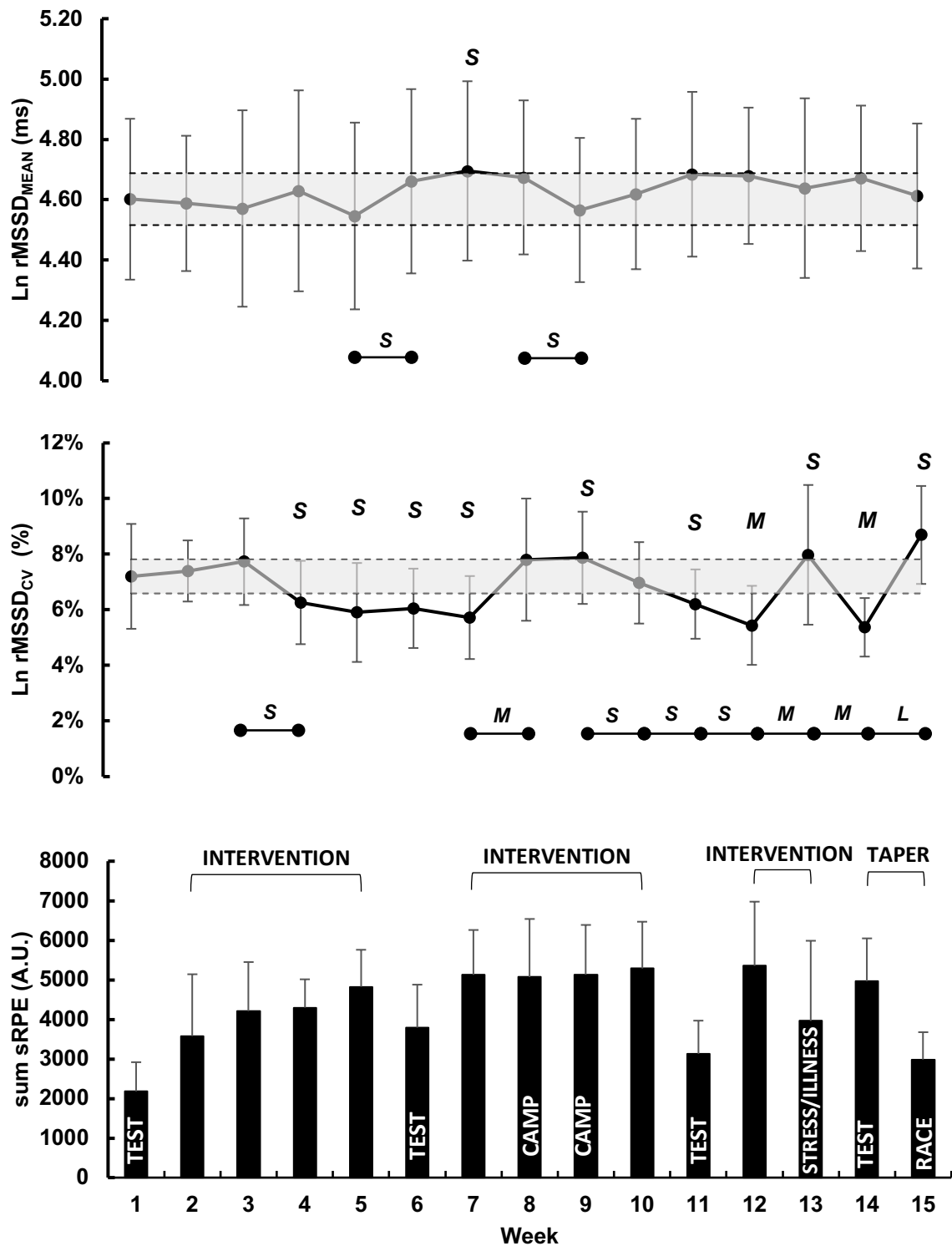


Figure 6.1. Weekly mean heart rate variability responses and mean sum of the sRPE for the 15-week period. Grey shaded area represents the smallest worthwhile change. S, M and L refer to small, moderate and large effect sizes, respectively. The effect size values reported below and above the “line of mean responses”, represent consecutive week-to-week changes and changes from baseline (week 1) values, respectively. Error bars represent 95% confidence limits for $\text{Ln rMSSD}_{\text{MEAN}}$ and $\text{Ln rMSSD}_{\text{CV}}$ and standard deviations for sRPE. Stress/illness refers to a week when majority of swimmers (i.e., $n=6$) experienced non-training related stress and/or illness.

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

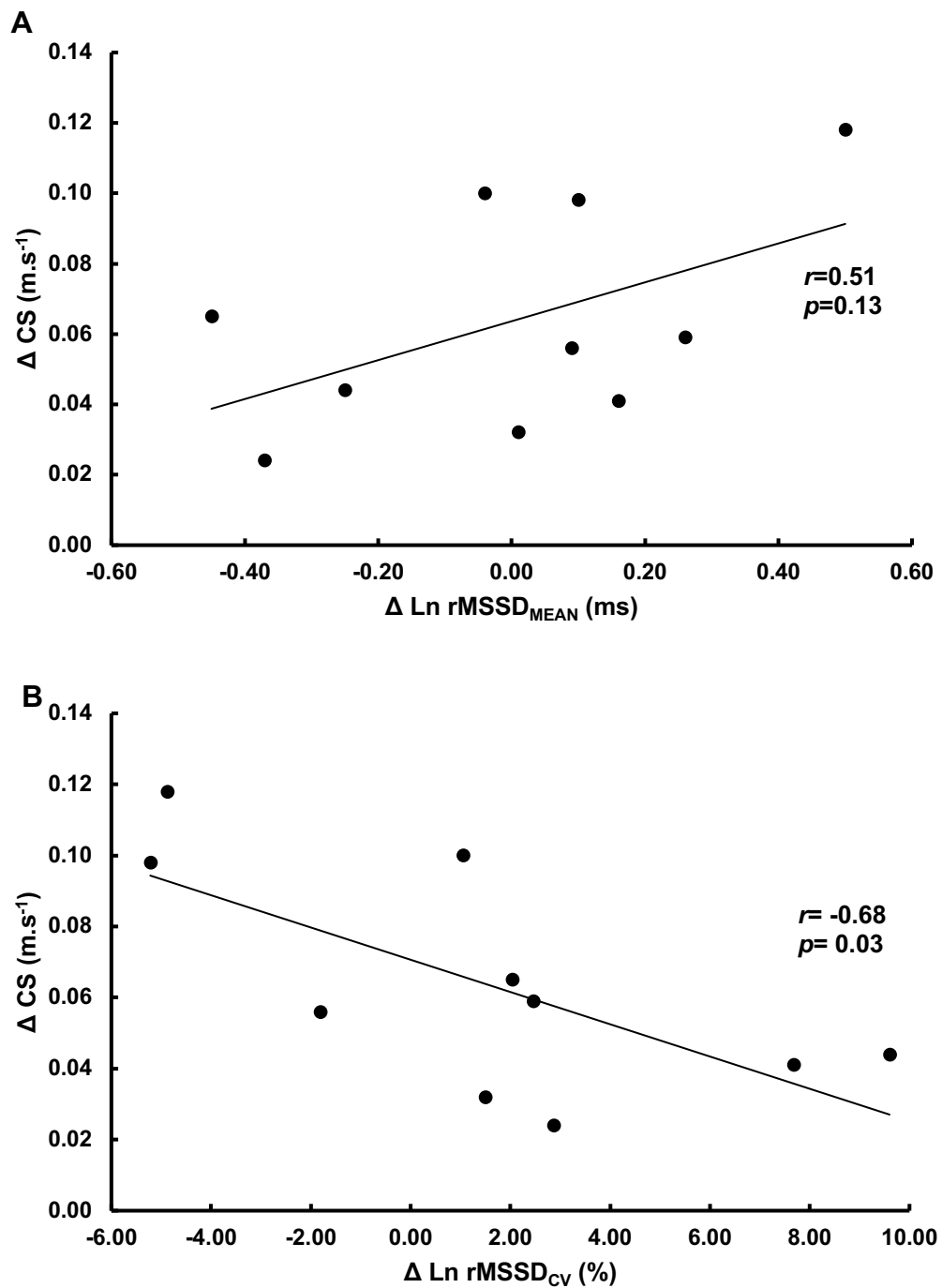


Figure 6.2. Relationships between seasonal changes (Δ) in critical speed and heart rate variability measures of $\text{Ln rMSSD}_{\text{MEAN}}$ (A) and $\Delta \text{Ln rMSSD}_{\text{CV}}$ (B) ($n=10$).

Chapter 6: Monitoring HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

6.4.3 Modelling HRV using sRPE

The mean and individual swimmers' values of the gain (k_1 and k_2) and time delay (τ_1 and τ_2) constants, and p are illustrated in **Table 6.2**. **Figure 6.3**, **Figure 6.4** and **Figure 6.5** illustrate model fit to actual $\text{rMSSD}_{42\text{-EXP}}$ data in individual swimmers when sRPE was used as the system's input. The IR model produced high goodness-of-fit (R^2) between modelled and actual $\text{rMSSD}_{42\text{-EXP}}$ (mean \pm SD: $R^2=0.66 \pm 0.25$; $\text{SSE}= 2278 \pm 2025$ ms), with individual R^2 values ranging from 0.21 to 0.98. R^2 greater than 0.75 was observed in six out of ten subjects.

6.4.4 Modelling HRV using sRPE and subjective wellness scores

Table 6.3 illustrates a mean model fit improvement when sRPE dataset was combined with different subjective wellness measures as the system's inputs to model $\text{rMSSD}_{42\text{-EXP}}$. Mean R^2 improvements in the range of 4-21%, representing *trivial-to-moderate* effects, were observed when sRPE was combined with one of the subjective wellness measures. Out of all investigated subjective wellness parameters, only the addition of mental energy and motivation wellness score to sRPE resulted in statistically significant improvement in the model fit. Additionally, the combination of sRPE with the subjective parameter which resulted in the best model fit within individual swimmers resulted in statistically significant improvement in the model fit. **Figure 6.3**, **Figure 6.4** and **Figure 6.5** illustrate a model fit improvement when sRPE and the best subjective wellness measure for each individual were combined.

Table 6.2. Estimates of model parameters using the Banister model.

Swimmer	p (ms)	k_1 (AU)	k_2 (AU)	τ_1 (days)	τ_2 (days)
S1	107	0.064	0.064	12.09	9.92
S2	49	0.038	0.038	60.00	58.07
S3	122	0.006	0.003	5.19	4.00
S4	44	0.047	0.047	25.08	24.35
S5	150	0.049	0.052	11.51	11.50
S6	92	0.006	0.006	22.26	19.01
S7	109	0.010	0.010	19.01	16.21
S8	212	0.017	0.017	60.00	59.90
S9	131	0.031	0.032	44.19	44.10
S10	117	0.007	0.009	36.93	28.88
Mean	113	0.027	0.028	29.63	27.59
SD	48	0.021	0.022	19.81	19.97

p , initial level of $rMSSD_{42-EXP}$ component of HRV; k_1 and k_2 , multiplying factors for the positive and negative component of HRV, respectively; τ_1 and τ_2 : time constants of decay for positive and negative components of HRV, respectively.

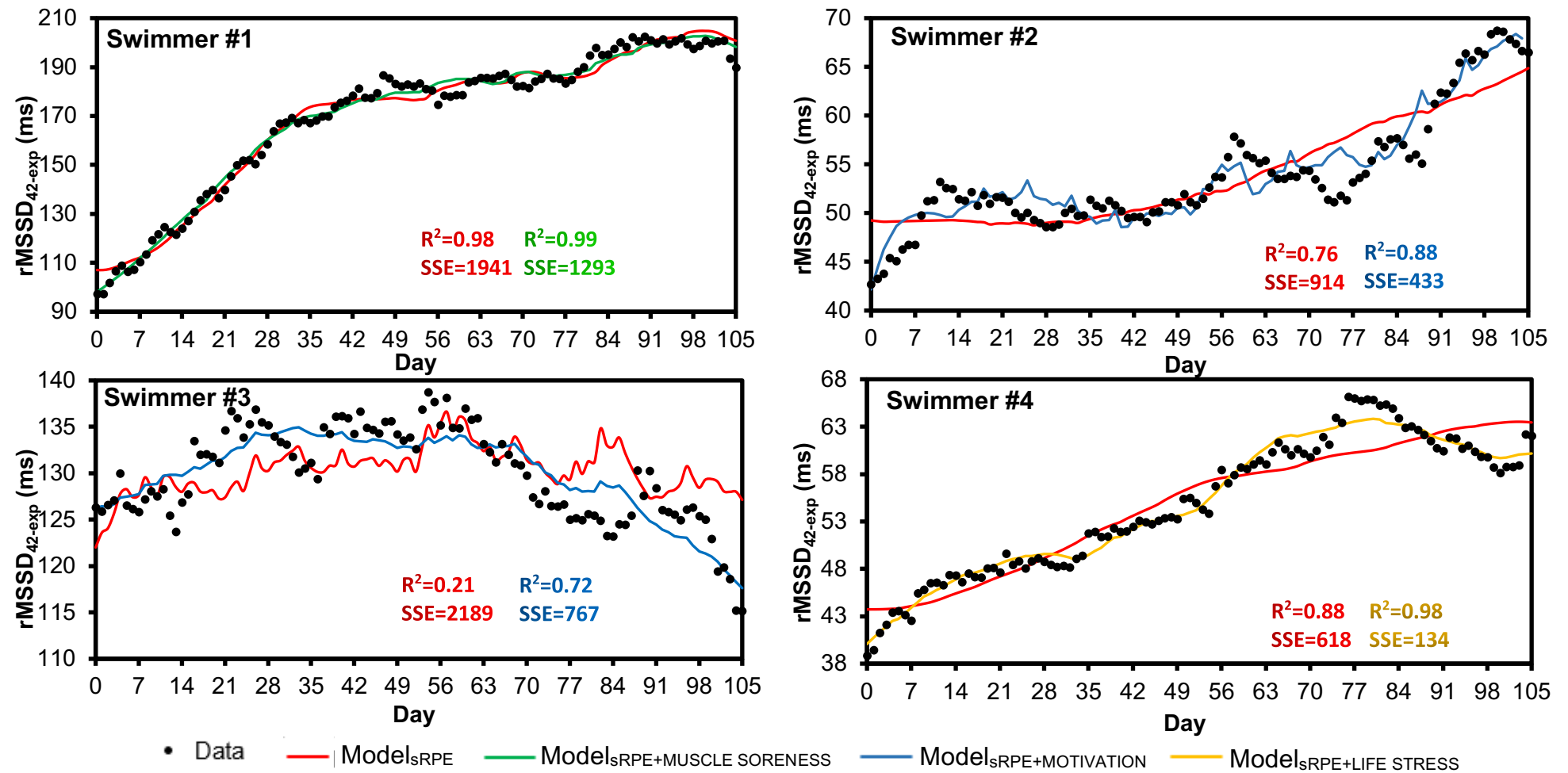


Figure 6.3. Modelling HRV responses using sRPE alone and in combination with the best subjective wellness score in the swimmers 1-4.

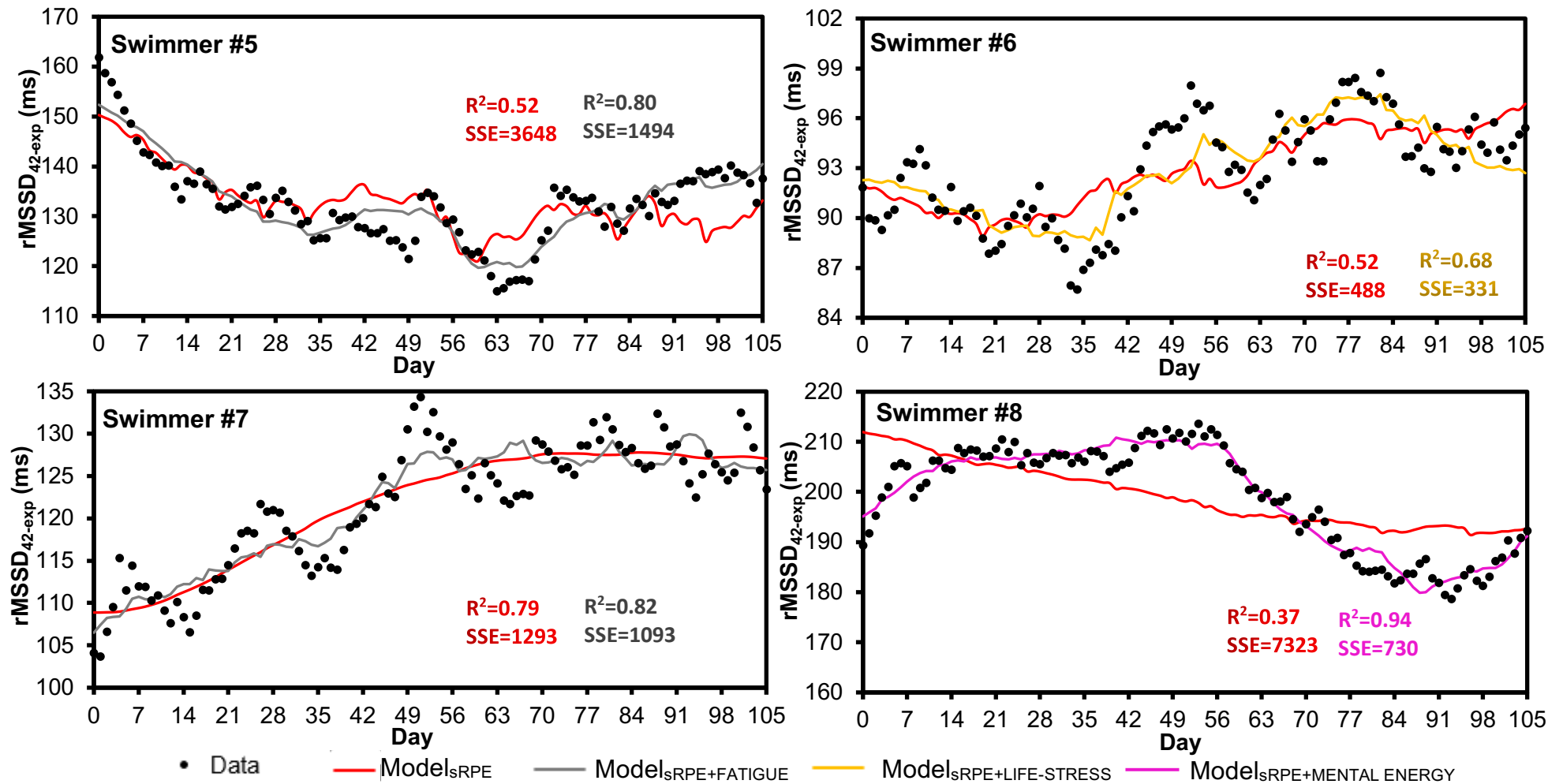


Figure 6.4. Modelling HRV responses using sRPE alone and in combination with the best subjective wellness score in the swimmers 5-8.

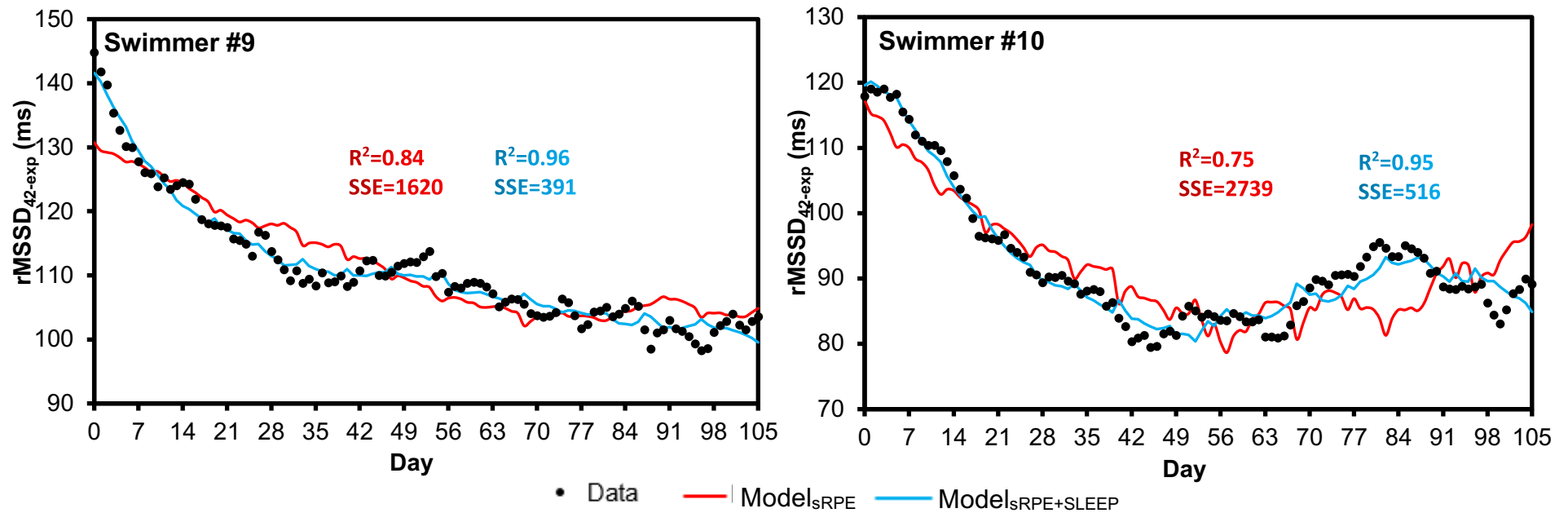


Figure 6.5.Modelling HRV responses using sRPE alone and in combination with the best subjective wellness score in the swimmers 9-10.

Table 6.3. Comparison of the model fit (R^2) when sRPE in combination with subjective wellness scores is used to model HRV responses.

Subjective wellness parameter	Model fit - R^2 (%)				
	sRPE only	Combined model	Improvement	p	Effect size
Life stress (n=7)	64±28	79±16	15±18	0.07	0.64 (moderate)
Mental energy (n=9)	64±25	80±21	16±17	0.01	0.67 (moderate)
Motivation (n=10)	66±25	82±17	16±20	0.01	0.77 (moderate)
Sleep quality (n=8)	72±24	75±30	4±11	0.12	0.13 (trivial)
Fatigue (n=7)	72±21	79±17	7±23	0.18	0.37 (small)
Muscle soreness (n=7)	68±28	87±9	19±24	0.09	0.91 (moderate)
Individuals' best marker (n=10)	66±25	87±11	21±19	0.01	1.10 (moderate)

6.5 Discussion

The principal finding of the present study is that HRV, as a representative marker of training adaptation, can be modelled effectively using an IR model and sRPE training load. These metrics can be collected in a resource and time-efficient manner by using a smartphone application available to all swimming programs. Additionally, when sRPE was combined with different subjective wellness measures as the system's input, the fit of the model to the HRV data improved in the range of 4-21%, representing *trivial-to-moderate* improvements. Finally, whilst changes in Ln rMSSD_{MEAN} and Ln rMSSD_{CV} were statistically non-significant, based on effect size statistics the following changes were observed: 1) A *small* increase in Ln rMSSD_{MEAN} was observed in the first recovery week when compared to the final week of the first intervention block (week 5-6). The Ln rMSSD_{MEAN} remained elevated and above baseline in week 7, after which a *small* decline in Ln rMSSD_{MEAN} was observed during overseas training camp (week 8-9); 2) After the first two weeks of training intervention, there was a *small* reduction in Ln rMSSD_{CV} from week 3 to 4 after which, Ln rMSSD_{CV} remained stable and below baseline values until commencement of an overseas training camp, where a *moderate* increase in Ln rMSSD_{CV} was observed. Once swimmers returned to normal training schedule (week 10), *small* week-to-week reductions in Ln rMSSD_{CV} were observed up to the start of week 13 ("stress/illness" week). In this week a *moderate* increase in Ln rMSSD_{CV} was observed compared to week 12 which was also above baseline values (*small* effect). However, during taper the Ln rMSSD_{CV} declined *moderately* below the previous week's value as well as baseline value. In competition week (week 15), a *large* increase in Ln rMSSD_{CV} was observed compared to taper week, which also represented a *small* increase above baseline values. When the seasonal changes in the aforementioned HRV measures were related to the corresponding seasonal changes in CS, large correlations were observed, indicating that athletes who experienced larger increases in Ln rMSSD_{MEAN} and decreases in Ln rMSSD_{CV} achieved greater improvements in CS.

A high goodness-of-fit between predicted and actual rMSSD_{42-EXP} data ($R^2=0.66 \pm 0.25$) was observed in the present study. This is, however, lower compared to the findings of Chalencon et al. (2012) who observed an R^2 of 0.79 ± 0.07 between modelled and actual HRV in a group of ten competitive swimmers. This is somewhat

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

surprising considering that the HRV methods utilised in the present study are more widely recommended methods for use compared to those utilised by Chalencon et al. (2012) (Buchheit, 2014; Plews et al., 2013a; b; Hynynen et al., 2011). Specifically, Chalencon et al. (2012) collected only one weekly HRV measure as opposed to collecting and averaging daily measures, which is currently considered as the best-recommended practice to avoid misleading results (Plews et al., 2013a). The authors also utilised the HF component of HRV as opposed to rMSSD, which is often proposed as the most reliable and practical HRV measure (Plews et al., 2013a). The lower model fit observed in the present study could, however, be attributed to taking morning measures as opposed to nocturnal measures which tend to be affected by psychological stress to greater extent than nocturnal measures and therefore could have added extra variance into the model in the present study (Hynynen et al., 2011). Alternatively, instead of attributing lower model fit to the system's output, the lower goodness-of-fit in the present study might be related to the inaccuracies associated with the data utilised as the system's input. Indeed, the calculation of the training load was different between the present study and Chalencon et al. (2012). Specifically, the authors calculated training load as the sum of the number of pool-kilometres swum and the dry land workout equivalent, which were exponentially weighted by specific coefficients according to seven training intensities. The present study used sRPE, which is considered to be a valid method of calculating training load (Haddad et al., 2017). However, it may be that this approach was not able to capture the training load as effectively as the method utilised by Chalencon et al. (2012). Nonetheless, it is important to note that one of the main aims of the present study was to explore whether a simpler method, which is already widely utilised by coaches, can be used to model HRV, as the complexities associated with the training load collection method utilised by Chalencon et al. (2012) would likely require more resources, time and expertise. It is also important to note that the model fit to actual data exceeded the threshold for a very large correlation in eight out of ten swimmers, of which three swimmers' profiles had nearly perfect relationship. This would result in the similar average model fit as observed by Chalencon et al. (2012) ($R^2=0.76$ vs. $R^2=0.79$), if the two swimmers with the poor model fit were excluded (i.e., swimmers #3, #8). Interestingly, the poor model fit was observed for the swimmers who experienced major stress-related situations during the study period, which could explain why the model fit was poor in these

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

subjects, given the impact of stress on HRV (Flatt, Esco and Nakamura, 2018; Hynynen et al., 2011). Additionally, nearly all swimmers in the present study attended a training camp abroad and experienced short-term illness (mainly upper respiratory tract infection) at some point during the study, which are known to impact HRV (Flatt, Howells and Williams, 2019; Hellard et al., 2011), and could therefore have compromised the accuracy of the model fit. Although, sRPE might be influenced by similar factors as HRV to some extent (Haddad et al., 2017), this method itself might have not provided a sufficiently good system's input to account for all stressors experienced by the swimmers, especially by those who experienced major non-training-related stress. However, when subjective wellness scores were combined with sRPE as the model's input, the accuracy of the model to fit the collected HRV data improved in the range of 4-21%. This consequently matches or exceeds the average model fit observed by Chalencon et al. (2012) despite using more feasible procedures (R^2 : lifestyle stress=0.79; mental energy=0.80; motivation=0.82; sleep quality=0.75; fatigue=0.79; muscle soreness=0.87; individuals' best marker=0.87). As an example, when the subjective lifestyle stress data were combined with sRPE for the two swimmers with the poor model fit, the R^2 increased from 0.21 to 0.55 in the swimmer #3 and from 0.37 to 0.80 in the swimmer #8. It is important to note that whilst the addition of selected subjective measures improved the model fit, it is not possible to make recommendation as to which wellness score modelled the HRV the best, due to the inconsistent number of subjects in the investigated conditions. However, based on the collected data, we observed that the magnitude of model fit improvement when using investigated subjective scores is likely athlete dependant as illustrated in **Figure 6.3**, **Figure 6.4** and **Figure 6.5**. Consequently, it can be concluded that whilst the model fit to collected HRV data was good when sRPE only was used, combining training load with subjective wellness measures as the system's input modelled HRV responses more accurately. This therefore provides further evidence for incorporating multiple measures when modelling responses to training. Indeed, whilst attractive in its simplicity, one of the limitations to the use of the original IR model is that the model assumes that responses to training are a result of training load and are linear (Hellard et al., 2006). Considering that responses to training are non-linear, highly individual and determined by the interaction of several variables rather than just training load (e.g. training history, sleep, stress, nutrition), future research should

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model
utilise multifactorial monitoring approach/machine learning methods (e.g., Neural Networks) to model and predict responses to training more effectively (Crowcroft, 2019; Mitchell et al., 2020; Edelman-Nusser, Hohmann, and Henneberg, 2002; Carrard, Kloucek and Gojanovic, 2020).

In relation to the week-to-week HRV responses collected during the 15-week period, there was no statistically significant change in $\text{Ln rMSSD}_{\text{MEAN}}$ despite the programme including periods of overload, taper and travelling abroad, which have been shown to influence HRV (Flatt, Howells and Williams, 2019; Flatt, Hornikel and Esco, 2017; Plews et al., 2013a). This is in agreement with the study of Perini et al. (2006) who observed a non-significant change in HF monitored at the beginning and the end of a five-month swimming season in similarly aged swimmers, and Atlaoui et al. (2007) who observed non-significant changes in both HF and rMSSD measures despite highly-trained swimmers undertaking 4 weeks of intensive training period followed by 3 weeks of reduced training period. Our results are, however, in contrast with studies of Garet et al. (2004) and Flatt, Hornikel and Esco (2017), who observed significantly reduced HRV (22 and 6%, respectively) during an overload period, which either peaked or returned to baseline values during the taper in competitive swimmers. Importantly, both Garet et al. (2004) and Flatt, Hornikel and Esco (2017) established 'baseline' HRV values from the week preceding the overload period, whilst the baseline in the present study represented values collected in week 1 of the study period. Indeed, whilst not statistically significant, based on effect size statistics there was a *small* increase in $\text{Ln rMSSD}_{\text{MEAN}}$ once swimmers completed the final week of the first intervention block and were provided with a recovery week (i.e. week 5-6). Whilst this remained elevated in week 7 (i.e., the week preceding the camp), the swimmers experienced a *small* reduction in $\text{Ln rMSSD}_{\text{MEAN}}$ during the training camp period, after which $\text{Ln rMSSD}_{\text{MEAN}}$ changed only *trivially*. It is also important to note that the findings of non-significant differences across the monitored period are based on group values. Additionally, three swimmers did not attend the overseas camp, which could have masked the effects of this period on HRV. It is also often recommended that HRV should be interpreted on an individual basis, as athletes have their individual HRV 'fingerprint' and may react differently to training prescribed given the circumstances within which individuals perform (non-training related stressors, fitness, nutrition, etc.). Indeed, it can be seen from **Figure 6.3**, **Figure 6.4**

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model and **Figure 6.5** that whilst HRV in some swimmers stayed relatively stable, other swimmers' HRV either increased and/or decreased substantially throughout the monitored period. This could therefore explain why changes in $\text{Ln rMSSD}_{\text{MEAN}}$ were non-significant and mostly trivial when assessed on a group level. Stable or increasing HRV generally indicates athletes are coping well with the designed training whilst decreasing HRV could be indicative of athlete's inability to adapt to designed training/increased stress. Although training sessions were prescribed more accurately and in an individualised manner (see chapter 5), differences in the HRV responses of swimmers provide evidence that some athletes responded to the prescribed training better than the others. Indeed, Vesterinen et al. (2016a) recently showed that initial HRV values should be considered when designing training programmes for individual athletes, as the athletes who had higher baseline HRV values achieved greater adaptations in maximal aerobic speed after the 8-week high-intensity training programme than athletes with lower baseline HRV, whilst the athletes who had lower baseline HRV values benefited more from the 8-week high volume and low-intensity programme than the athletes with higher baseline HRV. Alternatively, the timing of an overload period or HIIT within the season appears important and should ideally coincide with the time when athletes' HRV is stable or trending positively (Vesterinen et al., 2016b; Kiviniemi et al., 2007). Given that this was not considered in the present study, as is often the case in applied practice where scheduling of overload period/HIIT is often determined based on coaches' subjective decisions/experiences, scheduling of HIIT and an overload period may have not been optimal in terms of regulating training load, recovery and stress in some athletes.

Similarly to $\text{Ln rMSSD}_{\text{MEAN}}$, the changes in $\text{Ln rMSSD}_{\text{CV}}$ were statistically non-significant, although $\text{Ln rMSSD}_{\text{CV}}$ appeared more sensitive to changes in the training programme. Based on effect size statistics, both decreasing and increasing trends were observed in $\text{Ln rMSSD}_{\text{CV}}$ across the study period. Specifically, after the first two weeks of training intervention, there was a *small* reduction in $\text{Ln rMSSD}_{\text{CV}}$ from week 3 to 4. This remained stable and below baseline values until commencement of an overseas training camp where a *moderate* increase in $\text{Ln rMSSD}_{\text{CV}}$ was observed. Once swimmers returned to normal training schedule, *small* week-to-week reductions in $\text{Ln rMSSD}_{\text{CV}}$ were observed up to the start of week 13 ("stress/illness" week). In this week a *moderate* increase in $\text{Ln rMSSD}_{\text{CV}}$ was observed, however this was

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

reversed in the following week (i.e., taper), where Ln rMSSD_{CV} declined *moderately*. The week 15 (i.e., competition week) was characterised by a *large* increase in Ln rMSSD_{CV}. Our results are somewhat in agreement with Flatt, Hornikel and Esco (2017) which is the only study to date examining the impact of overload and taper on Ln rMSSD_{CV} in swimmers. Specifically, over a 5-week period, Flatt, Hornikel and Esco (2017) observed significantly greater Ln rMSSD_{CV} during a 2-week overload period compared to the week preceding this period (6.7% vs. 10.1%; *moderate* increase), which returned to baseline values during a subsequent 2-week taper (6.4%). Given that Ln rMSSD_{CV} reflects day-to-day variation in HRV and is believed to represent the adaptation, fatigue/stress and recovery processes (Flatt and Esco, 2016; Flatt, Hornikel, Esco, 2017) the following suggestions could be made based on observed results: 1) reduction of Ln rMSSD_{CV} from week 3-4 and maintenance of reduced values up to week 7 could be indicative of positive responses to the designed programme (Flatt and Esco, 2016); 2) increase in Ln rMSSD_{CV} during overseas camp could be indicative of greater stress and decreased ability to cope with the designed training, probably due to the increased amount of training (especially gym) as well as the differences between training environments (e.g. time zones, temperature) (Flatt, Howells and Williams, 2019; Plews et al., 2013a); 3) upon arrival to home environment and return to normal training schedule Ln rMSSD_{CV} continuously declined indicating improved ability to cope with the training programme until week 13; 4) despite week 13 being a normal training week, increased Ln rMSSD_{CV} could be explained by non-training related stress or illness experienced by the majority of swimmers (Flatt, Esco and Nakamura, 2018; Hellard et al., 2011); 5) this was subsequently reversed in taper where the window of opportunity for physical and mental recovery was greater due to a reduction in training volume, greater sleep availability, and end of school term; 6) a *large* increase in Ln rMSSD_{CV} in week 15 is not surprising considering that this period required travelling, likely increased anxiety levels associated with the most important competition of the season and racing multiple times during the day over several days.

Finally, the analysis of the relationships between seasonal changes in the investigated HRV indices (Ln rMSSD_{MEAN} and Ln rMSSD_{CV}) and CS revealed large correlations, although the relationship of CS with Ln rMSSD_{CV} ($r=-0.68$) was stronger compared to Ln rMSSD_{MEAN} ($r=0.51$). Our findings are in agreement with Flatt and Esco (2016),

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

who observed that a greater decrease in Ln rMSSD_{CV} ($r=-0.74$) and increase in Ln rMSSD_{MEAN} ($r=0.50$) within the first 3 weeks of training period were related to greater performance improvements in a YoYo test completed by female soccer players in week 5 of the training programme. However, Plews et al. (2013b) observed greater correlations between changes in Ln rMSSD_{MEAN} and change in 10 km TT ($r=-0.76$) and maximal aerobic speed ($r=0.72$) after a 9-week training period. The differences between the present study and Plews et al. (2013b) could be related to the performance outcomes utilised to assess this relationship, or the fact that four swimmers experienced health issues in the weeks utilised to establish this relationship. Whilst CS is a performance-related measure, this parameter represents a sub-maximal intensity, and so HRV may have a stronger relationship with outcome measures of the tests that measure one's maximal capacity, such as time trials or performances in actual races. Although we examined actual race performance improvements achieved by the swimmers in the investigated season, the approach utilised did not allow us to effectively explore the relationships between changes in HRV and performance at corresponding times. Specifically, a life-time personal best (PB) time that was achieved by swimmers at different times prior to the study was utilised as baseline and the change in PB was established from the race in which the swimmers achieved their best performance in the monitored period. This subsequently corresponded to different weeks between athletes, and so to effectively examine a relationship between HRV and performance was not possible. To the best of our knowledge, the relationship between HRV indices and critical speed or power has not been investigated to date and so further studies are required to examine which performance parameter is best correlated to changes in HRV. Despite this, the findings of the present study provide further evidence for utilising a HRV-guided training approach to optimise training outcomes, which has been shown to elicit smaller day-to-day variation in HRV and superior adaptations when compared to non-guided, predefined training programmes (Javaloyes et al., 2018; Vesterinen et al., 2016b; Kiviniemi et al., 2007). For example, the recent study of Javaloyes et al. (2018) examined the effect of 8-week HRV-guided and predefined training prescription in well-trained cyclists and found that cyclists who engaged in HRV-guided programme significantly improved peak power output (5%), power corresponding with second ventilatory threshold (14%), and performance in a 40-min simulated TT (7%), whilst cyclists who followed a predefined programme

did not achieve significant improvement in any of the measured parameters, despite spending a greater proportion of their training time between the first and second thresholds. Similarly, Vesterinen et al. (2016b) observed significant improvements in 3000 m running performance in a group of well-trained runners who followed an 8-week HRV-guided programme (2%), whilst runners who followed a predefined programme did not achieve significant improvements in this test (1%), despite completing a greater number of moderate- and high-intensity sessions. Both authors of the aforementioned studies attributed these results to better timing of the high-intensity training sessions i.e., HIT is only prescribed when the athlete is in optimal conditions to perform it. The effect of HRV-guided training on swimming physiology and performance has not been investigated to date, however, the results from the present study provide some evidence for utilising this approach in swimming as well.

The present study has some limitations that must be highlighted. There was a lack of direct swimming performance measurements, which prevented us from examining relationships between HRV and performance responses in both modelling and the descriptive part of this study. In addition to this, the R code that was utilised to combine sRPE and subjective measures to model HRV did not work in some participants due to an unexplained error with the optimisation function. This resulted in an inconsistent number of subjects included in this part of analysis, and prevented us from making recommendations as to which specific subjective wellness measure improved the model-fit to the greatest extent. However, this might be athlete depended, and so for coaches, the HRV4Training application provides correlations between individuals' HRV metrics and their subjective well-being measures, which could be used to determine which well-being measure is most relevant for each athlete. A relatively small number of swimmers also represents a limitation in the present study. Originally, sixteen swimmers were recruited, however, six subjects were excluded due to insufficient compliance to one or more utilised methods or withdrawal from the swimming programme, consequently reducing the statistical power. An additional limitation may apply to the data utilised to establish the baseline, which corresponded to the week prior to beginning of the training intervention (i.e., week 1). Specifically, in this week the swimmers were tested on two occasions and this week also corresponded to commencement of the school term. Therefore, this period might have not been optimal for establishment of baseline values, which should be ideally

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model established under ‘normal’ conditions e.g., non-significant stress. Finally, although the swimmers were provided with instructions and a familiarisation period prior to the study to facilitate collection of optimal measurements at home, and all data were revised every morning to detect possible mistakes in the measurements, we did not directly supervise each swimmer. Therefore, some swimmers might have not acquired training load, subjective wellness and/or HRV data optimally on some occasions despite recording an ‘optimal’ signal, which could have compromised our modelling outcomes. It is however important to note that the approach of ‘no direct supervision’ was chosen to replicate approaches typically utilised and favoured in applied practice, where protocols need to be as resource and time-efficient as possible.

6.6 Practical applications

This study showed that HRV can be modelled effectively when simple methods such as sRPE and subjective wellness scores are combined in the IR model, which was originally proposed to model performance responses to training. Given that HRV is related to performance (Chalencon et al., 2012), inclusion of HRV could reduce the burden of repetitive performance testing, which currently limited the use of this model for monitoring and planning in applied practice. HRV responses can be modelled via the IR model in Microsoft Excel (available to download [here](#)), which can be also used to predict HRV in the future as previously demonstrated by Williams et al. (2018) and Chalencon et al. (2015). Given the technological advances, all required data could be obtained via a smartphone application and only 1-min HRV recordings were used and obtained via PPG method (i.e., phone camera) rather than heart rate straps. Considering that coaches and athletes often operate with limited resources, time or expertise, the approach utilised to collect data is feasible without compromising on validity, and is likely to enable greater compliance from athletes/coaches to complete daily measures. Although we did not examine the effect of a HRV-guided programme on swimming, the results from the present study provide some evidence for utilisation of this approach in swimming training. Specifically, although the training sessions in the designed programme were individualised based on regular testing, which represented an improvement compared to the methods previously utilised by the coach, given the relationships we observed between HRV and CS, as well as between-swimmer differences in HRV responses, it is clear that the swimmers responded and

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model benefited differently from the programme. Considering that the role of the coach is to provide athletes with a programme that allows individual athletes to maximise their potential, alongside regular physiological testing, HRV measures could allow coaches to take the principle of individualisation a step further. Specifically, as demonstrated by previous studies (Javaloyes et al., 2018; Vesterinen et al., 2016b), considering normal HRV responses specific to an individual, HRV systems (e.g., HRV4Training) can now assist coaches with decision making related to planning and optimal timing of high-intensity sessions or intensive blocks of training, which are typically standardised and prescribed subjectively in most swimming clubs. This approach can be especially useful in high-performing swimmers who often complete high training loads to achieve small but meaningful improvements, but also face an ever-lasting challenge of maintaining a healthy balance between training load and taking sufficient recovery time to avoid negative adaptations. Additionally, by estimating model parameters for individual swimmers, this can also assist practitioners in making better decisions as to what training and recovery strategies might work the best for individual athletes (Clarke and Skiba, 2013). Alternatively, given that these monitoring systems often collect data related to individual's recovery processes too (e.g., sleep quality, lifestyle stress), a combination of this data with training load and HRV can now assist sports practitioners with making more informed decisions as to what steps are required to optimise individual's HRV status, rather than opting for a reduction in training load as typically done. Indeed, this approach may only provide a short-term solution for athletes that are consistently under recovered from perspectives such as sleep or nutrition, or experience non-training related stressors, and so systems such as HRV4Training represent promising tools for sport science teams to optimise training and recovery status of individual athletes.

6.7 Conclusion

In conclusion, the results from the present study demonstrated that HRV can be modelled with good accuracy when simple methods such as sRPE and HRV collected via a smartphone application are utilised in the IR model. The accuracy to model the HRV responses improved meaningfully when subjective wellness measures were added into the model, suggesting the use of multiple variables when modelling HRV. Although, there were no statistically significant differences in weekly $\ln rMSSD_{\text{MEAN}}$

Chapter 6: Monitoring the HRV responses to training loads in competitive swimmers using a smartphone application and the Banister impulse-response model

or $\ln rMSSD_{CV}$, *small-to-large* changes were observed in these HRV parameters throughout the season, with $\ln rMSSD_{CV}$ appearing more sensitive to changes in training programme than $\ln rMSSD_{MEAN}$. Differences between HRV responses in individual swimmers were also apparent. Finally, seasonal changes in the investigated HRV parameters were related to seasonal changes in critical speed, providing further evidence for incorporating a HRV-guided training prescription approach to facilitate optimal training prescription in individual swimmers.

Chapter 7: General discussion

7.1 Introduction

The aim of this PhD thesis was to contribute towards bridging the gap between science and practice in the areas of testing, training prescription and monitoring in competitive swimming. Given the gaps we identified in the literature review, and with support from the experiential learning of swimming practitioners, novel research questions were formulated and subsequently addressed in chapters 3-6. The aim of this final PhD thesis chapter is therefore three-fold: 1) to summarise the main findings and highlight their originality within the current state of knowledge; 2) to discuss practical applications and to demonstrate the to-date and future potential research impact of this body of work; and finally, 3) to recommend areas for future research within this field.

7.2 Addressing the research questions

The ability of coaches to effectively conduct physiological testing and utilise this data to prescribe individualised training to a large group of swimmers on a regular basis has been a long-lasting issue in swimming, primarily due to the demanding resources, time, and expertise required to undertake such procedures (e.g., step tests, MLSS test). The application and determination of the parameters describing the well-known power-duration relationship from a single all-out exercise test was therefore an important stepping stone for sports practitioners when Vanhatalo, Doust and Burnley (2007) successfully validated the use of a 3-min all-out cycling test against the cumbersome traditional methods of determining CP and \dot{W}' . Given the simplicity of this test, the validity and practicality of 3MT was soon investigated and extended to several modes of exercise and utilised for various purposes (Jones et al., 2010). Despite the broad applicability of the CS concept and the potential of 3MT to make this concept more accessible for swimming practitioners, the first attempt to apply the 3MT to swimming only appeared in 2017. Tsai and Thomas (2017) assessed the validity of the 3MT against traditional methods and showed the promising potential of 3MT for assessment of CS in swimming, although this did not extend to D' . However, this study was subject to several potential limitations related to the performance level of participants, lack of appropriate familiarisation trials, and inconsistencies in time-trial data utilised for traditional assessment of CS and D' . In

addition to this, no studies to date have investigated the reliability of 3MT in swimming. This led to the formulation of the first research question, which was addressed in Chapter 3:

1. What is the validity and reliability of the 3-min all-out test in highly-trained swimmers?

Key findings:

- Speed in the last 30 s of 3MT levelled off and reached a plateau as originally observed by Vanhatalo, Doust and Burnley (2007), although stabilisation of speed occurred earlier than in other modes of exercise (i.e., ~90 s).
- There was a nearly perfect correlation ($r=0.95$, $p<0.0001$) and no statistically significant differences between the CS established from the 3MT and traditional methods, using both distance-time and speed-1/t models ($p=0.19$).
- Despite very large correlations observed between D' established from 3MT and both traditional methods ($r=0.79$, $p=0.002$), the D' established from 3MT was on average ~15% and ~12% lower compared to D' derived from distance-time ($p=0.02$) and speed-1/t models ($p=0.09$), respectively.
- There were nearly perfect relationships ($r=0.93-0.98$; $p<0.0001$) and no statistically significant differences between actual and predicted 200, 400, 600 and 800 m TT times when CS and D' from 3MT were utilised in the predictive TT calculation.
- Test-retest reliability of the 3MT was high for both CS ($r=0.97$) and D' ($r=0.87$) with coefficient of variation values representing ~1% and ~9%, respectively.

Given that the 3MT allowed for the reliable and feasible assessment of CS and D' in Chapter 3, the aim of the second research study (Chapter 4) was to extend the use of this test to the demarcation of the remaining exercise intensity domains, as previously shown in cycling by Francis et al. (2010). Specifically, Francis et al. (2010) utilised CP from 3MT and exercise intensity domain thresholds established from a cycling IST in order to establish predictive equations that could help cycling coaches to estimate the remaining exercise intensity domains from CP only. Conducting an IST in swimming is time-consuming, invasive, and requires a substantial amount of resources

and expertise, and so the community of swimming coaches typically choose to compromise on validity in favour of methods that require less time and resources. Indeed, one of the most widespread methods utilised amongst swimming coaches is the ‘beats below HR_{MAX} ’. This method is regularly taught as a part of coaching curriculums, despite the fact that this method has not been validated and the approach it utilises to prescribe intensity has been criticised for decades (Jamnick et al., 2020; Meyer et al., 1999). Given that the approach utilised by Francis et al. (2010) could represent a compromise between validity and feasibility, and could therefore be more appealing for swimming coaches as opposed to IST and BBM method, the following research questions were formulated and subsequently addressed in Chapter 4:

- 2. Can the 3-min all-out test be used to estimate exercise intensity domains in highly-trained swimmers?**
- 3. How accurate is the beats below HR_{MAX} method in determining exercise intensity domains of highly-trained swimmers?**

Key findings:

- The spectrum of exercise intensity domains was narrower compared to those observed in other modes of exercise, with LT and LTP occurring at 86% and 95% of maximal speed achieved in IST, respectively.
- LT, LTP and S_{MAX} were estimated to occur at 89%, 98% and 104% of CS established from 3MT, respectively.
- The application of these predictive equations to the CS data collected from 3MT and their subsequent comparison to actual thresholds established from IST resulted in no statistically significant differences ($p=0.93-1.00$), and nearly perfect correlations at LT ($r=0.92$), and LTP ($r=0.90$), and very large correlations at S_{MAX} ($r=0.88$; all $p<0.0001$).
- Large-to-very large correlations ($r=0.63-0.89$, $p<0.03$) were also found between LT and LTP (speed and HR) established from IST and the BBM method. However, the ‘50-40’ BBM and ‘30-20’ BBM utilised by coaches to establish the boundary between moderate-heavy and heavy-severe domains, respectively, produced significantly lower estimates than those established from IST (all $p<0.03$).

In the last decade, the application of the CS concept has been extended from testing to the prescription of a novel personalised HIIT, in which the target time intervals for a given distance are personalised based on indices related to individual's 'anaerobic' (partial depletion of D') and 'aerobic' (relative to athlete's CS) capacities (Pettitt, 2016). Whilst $\dot{V}O_{2\text{MAX}}$ is typically recommended for prescription of HIIT (Buchheit and Laursen, 2013), amongst swimming coaches, HIIT is typically prescribed based on more affordable methods (e.g., beats below HR_{MAX} , race-pace velocities, PB times, holding best average, all-out). These approaches, however, do not take into account the between-subject differences in anaerobic and/or aerobic capacities. As such, feasible methods that can better individualise HIIT are required to help coaches to optimise the training stimulus they prescribe. The CS concept may provide a solution to these issues, as CS and D' can be reliably obtained in a single session via the 3MT (chapter 3-4), and subsequently used to individualise training. Furthermore, the CS concept has the potential to extend the prescription of HIIT to focus on the development of race-specific technical proficiency, by using the CSR concept as a biomechanical surrogate of CS to prescribe HIIT. This approach challenges both the physiological and technical abilities of a swimmer by providing speed and stroke constraints (Dekerle et al., 2002). However, although promising evidence existed from studies that have applied this approach for a training cycle of 4-6 weeks, there was a need to examine the long-term application and impact of this type of HIIT on several parameters of swimming, in order to assess the effectiveness and feasibility of this concept in a regular competitive swimming team. In addition to this, how much training volume is needed to prescribe swimming training effectively has been an everlasting debate amongst swimming coaches and scientists. Indeed, despite accumulating evidence suggesting that lower-volume, higher-intensity focused training strategies (rather than higher-volume, lower-intensity) are more effective in achieving improvements in performance of competitive swimmers, many coaches still employ traditional high-volume practices with the belief that there is need for this amount to optimise physiological and technical adaptations in swimmers (Nugent et al., 2017; Nugent, Comyns and Warrington, 2017). Therefore, to contribute to this ongoing debate, it was necessary to examine whether a reduction in training volume 'compensated' with better individualised training programmes prescribed on the basis

of the CS and CSR concepts would be beneficial. Therefore, the following question was formulated and answered in chapter 5:

4. Can the data from 3MT be used to individualise a swimming training programme and see improvements in performance despite a substantial reduction in training volume in highly-trained swimmers?

Key findings:

- HIIT prescribed based on CS and CSR concepts 3 times.week⁻¹ for one short-course season (as 5 x 3 min intervals depleting 60% of D', 3 x 3.5 min intervals depleting 80% of D' and 10 x 200 m or 150 m at CS with 2 cycles.min⁻¹ lower SR than CSR) was associated with improvements in several important physiological, technical, and performance parameters in highly-trained swimmers, despite a $\geq 25\%$ reduction in training volume.
- CS increased by $5.4 \pm 1.6\%$ over the season, representing an *extremely large* effect size, and exceeding average seasonal improvements previously reported by similar research studies.
- D' decreased by $25.2 \pm 7.5\%$ (*very large* effect) over the season, an effect consistent with the findings of previous studies utilising similar HIIT design.
- The change in the PB times for the swimmers' 1st and 2nd main competitive events represented an improvement in time of $1.2 \pm 1.3\%$ (*small* effect) and $1.6 \pm 0.9\%$ (*moderate* effect), respectively, allowing the group of swimmers to score ~30 extra FINA points and swim closer to WR by ~1.4%.
- Compared to the performance improvement observed in the same swimmers and events in the season prior to the intervention (i.e., January-July season) (1st event: $-1.0 \pm 0.9\%$; 2nd event: $-0.7 \pm 0.8\%$), this improvement was similar to that achieved in the 1st event and ~2-fold greater in the 2nd main event, despite the intervention being implemented for a substantially shorter period of time (3.5 months) and with substantially lower training volume.
- Seasonal changes in SL@CS and SC@CS were trivial, suggesting that the swimmers were able to hold similar SL and SC despite swimming at higher CS.

Chapter 6 was an extension of the aforementioned intervention, throughout which swimmers also collected daily HRV responses, sRPE training load and several subjective wellness responses via a novel smartphone monitoring application. The development of such smartphone applications has opened the door to exploring various novel research questions. Firstly, daily recordings of HRV and changes in performance parameters such as CS would allow for a description of HRV responses of swimmers to a designed short-course training season, as well as their associations with seasonal changes in CS, which have not been explored to date. Secondly, having the aforementioned data would allow the replication of a promising novel monitoring approach utilised by Chalencon et al. (2012), who suggested that HRV can be used as a proxy to monitor changes in performance via the I-R model. If the approach employed by Chalencon et al. (2012) could be replicated utilising data collected via a novel smartphone app, this would create a monitoring system that would be substantially easier to implement for swimming coaches. Consequently, Chapter 6 explored and addressed the following research questions:

- 5. What are the typical seasonal HRV responses of highly-trained swimmers?**
- 6. Is there a relationship between seasonal changes in key HRV parameters and CS?**
- 7. Can sRPE be used to model HRV responses of swimmers utilising the I-R model?**
- 8. Does accuracy of model fit improve when subjective wellness measures are combined with sRPE in the I-R model?**

Key findings:

- Based on group responses, there were no statistically significant changes in key HRV parameters throughout the season, although *small-to-large* effect size changes were observed in these parameters (especially around overseas camp and taper period).
- Ln rMSSD_{cv} appeared more sensitive to changes in the training programme than Ln rMSSD_{MEAN}.

- There was high between-subject variability in HRV responses to the designed training programme, suggesting that swimmers responded differently to the programme despite better individualisation of their training stimulus.
- Large correlations between seasonal changes in CS and the investigated HRV parameters were observed, which possibly suggests the use of a HRV-guided training prescription to improve the principle of individualisation a step further.
- There was a high level of agreement between actual and predicted HRV responses when sRPE was used to model HRV responses utilising the I-R model ($R^2=0.66$). The model fit was improved further (R^2 values of 0.75-0.87) when different subjective wellness scores were added as system's input along with sRPE, subsequently matching or exceeding the model fit previously observed by Chalencon and colleagues, despite utilising more feasible and affordable methods for athletes and coaches.

7.3 The original contribution to knowledge

In order to make an 'original' contribution to knowledge, according to Madsen (1983) the work should fulfil one or more of the following requirements: 1) to uncover new facts or principles; 2) to suggest relationships that were previously unrecognised; 3) to challenge existing truths or assumptions; 4) to afford new insights into little understood phenomena; 5) to suggest new interpretations of known facts that can alter man's perception of the world around him. With these in mind, this thesis has made the following novel contributions to current knowledge:

- First study to assess validity and reliability of 3MT in highly-trained swimmers and to show 3MT is a valid, reliable and feasible assessment tool in applied swimming practice
- First study to assess validity of the beats below HR_{MAX} method and to show that this method underestimates boundaries of exercise intensity domains accompanied by large inter-individual differences
- First study to utilise 3MT to estimate exercise intensity domains in swimming and to show this can be used as an alternative approach for those practitioners that do not have access to IST on a regular basis

- First study to apply the CS and CSR concepts to training prescription and to describe performance, physiological and technical responses to this type of HIIT training in highly-trained swimmers over an extended period of time, showing this to be an effective approach to individualise training in swimming despite a substantial reduction in training volume
- First study to collect and describe daily/weekly HRV responses of swimmers over one competitive season including overload, overseas training camp, taper and competition phases
- First study to examine the relationship between seasonal changes in key HRV parameters and CS, showing large relationships between these parameters
- First study to utilise sRPE and subjective wellness scores to model HRV responses utilising the I-R model, showing that the I-R model and data collected via a novel smartphone application can be used to model HRV responses to swimming training and non-training related stressors

7.4 Practical applications and potential impact

The establishment and regular re-assessment of exercise intensity domains that are used to inform individualised training prescription are the key pillars on which training programmes of successful athletes often stand. However, the process of regularly (re)assessing and prescribing individualised training has always been especially challenging in swimming due to its multidisciplinary nature, the technical and environmental constraints that apply to testing in swimming pools, as well as the limited resources, time, and expertise often available to coaches in many swimming clubs. This has often forced coaches to utilise less valid (if any) testing processes or utilise valid processes but irregularly (~1-2 x season), which subsequently compromise the quality of a training programme the coaches can deliver. The 3MT swimming protocol utilised in this PhD has shown the potential to address some of these issues due to its validity, reliability and feasibility to apply in a regular swimming team involved in this PhD. Consequently, this work provides coaches with a promising and versatile tool that can be used for multiple purposes, assisting coaches in the delivery of arguably more effective training programmes. The scope for utilisation of 3MT include but are not limited to the following:

The 3MT allows for demarcation and assessment of key physiological and performance parameters for swimming (i.e., CS and D'), and can therefore allow coaches to monitor adaptations in the swimmers' physiological profiles elicited by a previous training block in a time and resource-efficient manner on a regular basis. This can be further extended by utilising the approach discussed in Chapter 4, which initially combines data from IST and 3MT in order to estimate where thresholds demarcating moderate and/or extreme domains occur in relation to CS. Depending on resources and thresholds of interest, coaches need only run one IST (or first stages of the test, if LT is the threshold of interest) in order to establish where these thresholds occur in relation to CS for their group of swimmers (level, main stroke(s)). These can be subsequently utilised as the estimates for the remainder of the season. Alternatively, without access to IST, coaches can use estimations from published data or from estimations predicted by their coaching peers, using comparable populations. Whilst, there are limitations associated with using these estimations to demarcate other thresholds from CS, research suggests that utilising CS/CP allows for the prescription of a more homogenous training stimulus compared to methods based upon maximal $\text{HR}/\dot{\text{V}}\text{O}_2$ such as beats below HR_{MAX} method used in swimming (Jamnick et al., 2020; Jamnick et al., 2018). Therefore, the aforementioned approach conceptualised in **Table 7.1** could represent a good compromise between validity and practicality of the methods and frameworks coaches could realistically use to inform their coaching plans on a regular basis.

Table 7.1. An initial conceptual framework of training intensity zones applying the critical speed concept in swimming.

Zone	Name	Physiological boundaries	Boundaries as % of Critical Speed	RPE boundaries	Description/Use
1	Moderate	Upper: lactate threshold	<90%	1-4	-Steady state is achieved in ~3 min -Used for development of base fitness and technical skills/ warm up/ cool down/ recovery sessions
2	Heavy	Lower: lactate threshold Upper: critical speed	90-100%	5-6	-Steady state in blood lactate and $\dot{V}O_2$ is achieved in ~15-20 min -Used for development of physiological efficiency (oxidative and glycolytic) with stable technical parameters -Can be also used for improvement of technical efficiency utilising CSR concept
3	Severe	Lower: critical speed Upper: highest speed that elicits $\dot{V}O_{2MAX}$	100-105%	7-9	-Steady state in blood lactate and $\dot{V}O_2$ cannot be achieved, accompanied by D' depletion, and $\dot{V}O_{2MAX}$ is achieved if sufficient time is provided, time to fatigue is also highly predictable when CS and D' are combined -Used for development of critical speed and $\dot{V}O_{2MAX}$, and race specific technique -HIIT (e.g. depletion sets, HIIT efficiency sets using CSR)
4	Extreme	Lower: highest speed that elicits $\dot{V}O_{2MAX}$ Upper: maximal sprinting speed	105%-maximal speed	10	- $\dot{V}O_{2MAX}$ cannot be achieved/rapid depletion of D' -used for development of D', peak speed and race specific elements (stroke, starts, turns, finishes)

Importantly, the results from 3MT can be used further for regular (re)prescription and individualisation of swimmers' training, as demonstrated in Chapter 5. Furthermore, the scope for different designs of training utilising CS and CSR concepts is substantial and can be largely determined by the creativity of coaches and determining factors in swimmers' specialised events. As an example, in D' depletion schemes, coaches can modify depletion rates/duration/distances/number of reps and sets. HIIT efficiency sets can be run in two main formats, or of their combination, in which swimmers are either asked to swim at CS with a lower SR than CSR (as in chapter 5) or difficulty can be increased by asking swimmers to maintain CSR but swim faster than CS (i.e. severe domain), both of which provide swimmers with race-specific physiological and technical stimuli/challenges simultaneously. Indeed, given that the data used to prescribe this type of training is specific to an individual's physiological and technical capacity, coaches utilising these concepts could achieve better individualisation and standardisation of a training stimulus compared to the methods typically utilised by coaches, which do not necessarily anchor training zones effectively and are also typically standardised over the same distances and/or with similar turnaround time regardless of swimmers' fitness or stroke specialty. It is important to note that the application of 3MT could become especially useful in swimmers specialising in individual medley or more than one stroke, given that these swimmers need to maximise improvements in multiple strokes that have specific energetic demands. Currently, testing of all four or at least two strokes on a regular basis is seen very rarely in swimming practice and so training programmes for these swimmers could be arguably made more effective. Additionally, given that coaches often prescribe leg and arm-only swimming, 3MT can provide coaches with useful data to monitor improvements in these separate elements as well as more specific training prescription.

Although not applicable for all coaches and athletes, given that elite swimmers often integrate altitude training into their programmes, data extracted from 3MT also has the scope to facilitate successful and effective completion of this training element, which often proves challenging for many coaches. Indeed, it is well known that altitude training (hypoxia) impacts on thresholds demarcating exercise intensity domains (CS and D'), which along with high inter- and intra-individual responses increase the risk of misguided exercise prescription and possible maladaptation if not

considered effectively (Townsend et al., 2017). However, conducting extensive testing to explore the impact of these conditions on swimmer's physiology can be challenging due to the resources and time available to coaches, and so consequently some coaches often rely on experience. Therefore, 3MT testing could help coaches to better account for the impact of this training on athletes' training prescription and account for differences between athletes, which could consequently allow for more effective training prescriptions whilst utilising minimal resources and precious time for testing.

As demonstrated in Chapter 5, data extracted from 3MT also has the scope to optimise and individualise swimmers' warm up strategies. Given previous research on the positive effect of priming in the severe exercise domain to subsequent severe-intensity exercise, the CS and D' established from 3MT can be also used to individualise and optimise swimmers' warm ups prior to races or HIIT, whilst controlling for intensity and depletion/repletion of D'. Based on the initial findings of Bailey et al. (2009) and Ferguson et al. (2010), a 'priming' set accumulating ~6 min of severe intensity exercise with D' depletion rate of 60-80% could be integrated at the end of swimmers warm up and followed by 20-30 min recovery in order to allow swimmers to prepare for the race, replenish utilised D' whilst still benefit from priming effects. This, however, only represents a starting point and so coaches should be encouraged to explore this with individual swimmers to finalise a design that will allow them to optimally prepare, both physiologically and mentally.

Broader applications of data derived from 3MT could also extend to informing future training processes, event selection, talent identification or informing racing/pacing strategies (Jones et al., 2010). Specifically, collection of normative CS and D' data specific to events and level of swimmers can be used to inform coaches as to what parameters the swimmers should work on as a priority in order to develop a similar physiological profile to the swimmers performing at the highest level in the same event. Alternatively, this data can help coaches with event selection for the athletes or talent identification processes. Finally, understanding swimmers' CS and D' can be utilised to inform preparation of pacing/racing strategies, which perhaps applies the most for the swimmers who specialise in longer events (400 m- 10 km).

Although not illustrated extensively in this PhD, based on our latest experience with 3MT in practice, coaches can even use 3MT for the assessment of swimmers' turning

skills, which are fundamental contributors to swimming performance. Specifically, given that time for 10 m sections are collected in 3MT, this test can provide coaches with information such as times into and out of the turns throughout the test as well as the drop off in these times as a swimmer fatigues, therefore allowing coaches to monitor progress and identify what aspects need to be worked on in order to allow individual swimmers to progress with their overall swimming performance.

Given the aforementioned areas of 3MT application, it is therefore believed that the 3MT represents a promising tool which, if added into a ‘toolbox’ of the swimming coaching community, could help tackle a wide variety of questions and issues currently faced by swimming coaches. Indeed, to the best of our knowledge there is no swimming test other than 3MT that has the capacity to inform on the variety of aforementioned aspects of swimming, whilst allowing for the assessment of physiological profiles in a large group of swimmers in a short time (~20 tests in 2 hours) and with minimal resources. Therefore, 3MT represents a promising tool that has the potential to facilitate a shift in more effective and regular testing and prescription of training for coaches and athletes regardless of their level and amount of resources, time and expertise available.

Although we did not directly examine whether high training volumes programmes are more effective than lower-volume higher-intensity focused programmes, we provided some evidence that longer term reductions in volume, when replaced by better individualisation of training, could be one of the ways forward for the community of swimming coaches. This especially applies for coaches who have limited pool time and need to maximise this, or for those coaches that advocate the need for very high training volumes in order to maximise swimmers’ potential. Whilst coaches delivering traditional high-volume programmes can equally integrate the investigated concepts into their coaching practice, it is important to note that the ‘high volume’ coaching philosophy in swimming has been increasingly questioned over the last decade, and has been repeatedly identified as a cause for a wide array of overuse injuries, burnout, dropout and early specialisation in swimming (Nugent et al., 2017). Therefore, it is hoped that the findings of this PhD also have the potential to improve these training practices and facilitate a shift in the perception that high training volumes are a requirement for success in swimming.

Last but not least, it is important to note that despite improved prescription of training across the investigated season, we observed that swimmers benefited differently from the training programme, as evidenced through between-swimmer differences in responses in several parameters, including HRV, as a global marker of training adaptations (Plews et al., 2013a;b). Given the accumulating evidence that supports a HRV-guided training approach over traditional predefined prescription (Javaloyes et al., 2018; Vesterinen et al., 2016a;b; Plews et al., 2013a;b), it is important to acknowledge that the training approach utilised in Chapter 5 did not allow all swimmers to maximise the training period. This could be related to the timing of sessions and blocks, which were mostly predetermined by the coach in advance, as is typically done in practice. In order to optimise the delivery of a training programme, it is therefore clear that individualising training intensity is not sufficient, and coaches could take the principle of individualisation a step further by using HRV monitoring systems. Substantial advances in smartphone technology, such as the HRV4Training app (utilised in Chapter 6), have enabled coaches to gauge the readiness of an athlete to absorb and benefit from pre-planned training stimulus or inform athletes about the need to step back and address other issues typically related to better management of training load or recovery processes (nutrition, sleep, life stress). Until recently this monitoring process has been difficult to implement for most coaches. The affordable and easy-to-use HRV monitoring apps can now assist coaches with answering the aforementioned question and allow them to be more objective and proactive to the processes taking place on a daily basis. Finally, it is important to emphasise that whilst this research was conducted in a swimming setting, multidisciplinary sports that involve swimming disciplines such as triathlon, aquathlon, water polo or pentathlon could equally benefit from the findings of this body of work.

7.5 Research impact

Given that the overarching aim of this PhD was to produce a body of work that could mainly help swimming coaches, throughout this PhD several projects and collaborations were simultaneously run in order to maximise the impact of this body of work in a community of swimming coaches and organisations whilst at the same time obtain valuable feedback from this community.

Firstly, the performance swimming academy and head coach, who allowed us access to their highest performing group of swimmers throughout this PhD, have decided to implement the investigated approaches across the training programmes of all groups of swimmers (county-international). The academy has been running testing sessions approximately every month for the highest performing group of swimmers (n=20) whilst remaining swimmers (n=40) are tested every ~2-months. In addition to this, all coaching staff have attended workshops to understand the theory behind 3MT and how to implement it within their practice. Over the 3-year collaboration, the team has become one of the most successful swimming academies in the UK and is continually enabling an increasing number of swimmers to meet the qualification standards for national championships, where most swimmers compete amongst the best in finals or reach medal positions.

In 2018, a new collaboration with Danish Swimming was created as a result of the publication of Chapter 3 and 4. Specifically, the research team was contacted by the head of an advisory panel for Danish coach education, asking to host their two national head swim coaches in Bath. These coaches were completing a one-year project in order to receive the highest coaching level award in Denmark and so had been asked to visit high performance training centres and collate information about new testing and training practices within swimming. These coaches and their swimmers were hosted in Bath for a week, where they had an opportunity to see and learn about the 3MT test and CS concept and its application in day-to-day training. Upon completion of this visit, we were subsequently contacted by the head of coach education for Danish Swimming, who suggested a further collaboration. This involved delivery of a workshop discussing our work at the annual national swimming Danish conference, which was organised for ~100 selected coaches. This resulted in a further collaboration with several other coaches and teams, with which we are currently working with to embed the findings of this PhD into their daily practice. During this time a similar collaboration was created with the Slovak national swimming team, which asked us to test their swimmers and present the findings to a group of coaches coaching both junior and senior national teams. This organisation also asked us to contribute to the creation of a new coaching curriculum for coach education qualifications.

Following the completion of Chapter 5, the swimming academy in Bath has started to host several Swim England Coach Qualification courses where the approaches utilised were discussed with the course leader and all attendees. The new approaches and results sparked a lot of interest amongst coaches and motivated our team to begin to create material and start running coaching workshops in which coaches can gain understanding of both the science behind the utilised approaches as well as run through practical processes such as 3MT testing and its analysis and application in the pool.

More recently, we have started a collaboration with a swimming researcher and practitioner in Australian Swimming and the Queensland Academy of Sport, who visited the University of Bath and swimming academy in November 2019, to discuss our research and see its application in a training environment. As a result of this, we have been invited to visit Australia, supported by the *Santander Research Grant*, to present our work to coaches and other sports practitioners and have agreed to work on several collaborative projects with the aim to help the community of swimming coaches further. In addition to this, we have collaborated to create a new 3MT ‘shiny App’, which can be used by coaches to analyse 3MT data immediately and without the need to necessarily complete and understand all processes behind the analysis. Importantly, building on my practical experience working with a wide range of swimmer’s abilities over the course of this PhD, this app now uses a slightly different and potentially more valid and reliable approach to extract CS and D’ data. Specifically, the CS is now consistently calculated as the average speed in the last 50 m of the 3MT. The duration of the 3MT now extends to 3 min and 10 s in order to allow the capture of a full 10 m split at the end of the test. This approach was chosen as the original approach utilising the last 30 s to calculate CS could result in varying distances being covered in the last 30 s, which in some situations may or may not capture turning, thereby compromising the ecological validity. Therefore, the 50 m method makes the CS calculation more consistent between swimmers and applies better to actual training prescription in the pool set-up, which always involves consistent lap lengths with turning. D’ is now calculated using the mathematical model recently proposed by Michell et al. (2018a), which uses an exponential function to fit speed-time data and calculates D’ as the area under the curve but above CS. Indeed, whilst this approach requires future validation (currently in process), based on our and other coaches’ experiences, this approach appears to allow more accurate training

prescription of training sessions such as depletion schemes in HIIT and work at CS (i.e. swimmers can swim times within 1 s of prescribed times and are not able to complete more than prescribed number of repetitions of intervals, signalling depletion/exhaustion; in HIIT efficiency session, swimmers can comfortably swim at CS for ~30 min).

It is important to mention that all aforementioned collaborations have allowed us to collect data across different levels of swimmers specialising in different distances and strokes. This has allowed us to create normative values for CS and D', which coaches could use as resource to see what values to aim for considering the specific event, performance level and sex of a swimmer. Furthermore, over the PhD period we have conducted numerous ISTs and 3MTs in all strokes, and so once a sufficient number of tests in each stroke is achieved, resources that could be used by coaches who do not have the time, resources or expertise to estimate their own thresholds of exercise intensity domains from CS will be created. Finally, over this time we created a training prescription sheet that can be used by coaches to prescribe several types of individualised training sessions based on the data collected from 3MT testing. This was created in order to make the process of embedding and utilising these approaches as easy as possible for coaches. To make the process of actual 3MT testing easier, we recently validated the use of a stopwatch app, which allows automatic transfers of time splits into a 'csv' file. This consequently reduces the need for coaches to manually transcribe the splits from stopwatch to a computer (also reducing transcription errors), and so the coaches can now test 10 more swimmers compared to the original set up (i.e., ~30 tests in 2 hours in one lane). The collected data can be directly inserted into the 3MT shiny App, and so coaches are only required to insert new CS and D' data into the prescription sheet, which is already pre-programmed with required calculations, thereby allowing coaches to individualise training sessions for the following training cycle in a very short space of time.

Finally, throughout this PhD we also contributed to several sources of material designed to inform the community of swimming and triathlon coaches about the latest practices in swimming. As an example, we contributed to *Swimming Science*, which is one of the most popular education resources (podcasts) for swimming coaches, we provided an interview for *Triathlete US* considered as 'the world's number one

triathlon magazine', and we have recently been asked to write a book chapter on the use of the CS concept and 3MT for swimming practitioners. Therefore, it is hoped that in the given timeframe we have successfully reached a significant body of swimming coaches, which we will aim to continuously grow in the coming years.

7.6 Future research

As highlighted throughout this PhD, most of the research questions proposed in this thesis were answered for the first time. Indeed, although the CS concept and 3MT has been researched and available to practitioners for decades, its application in swimming has not been as extensively explored despite its potential highlighted above. Consequently, the scope for future studies is vast and is not limited to the following:

Firstly, future studies could assess the validity of 3MT further by examining physiological responses at and/or ± 2.5 -5% of CS. This would confirm that the derived CS truly represents a boundary between sustainable and non-sustainable domains, alongside the corresponding physiological responses that characterise these domains. Additionally, this could be further supported by investigating the predictive validity of the parameters derived from 3MT in TTE trials swam at set speed above CS (e.g. 105% of CS). Future studies could also explore the application of 3MT in both types of swimming pools (25 m and 50 m), which would allow for the examination of differences between extracted CS and D' values from different pool set-ups. This would enable the calculation of estimation equations to help coaches to convert values in between pools without the need to complete 3MT tests in both pools (currently in process). Future studies should also aim to further explore the application of 3MT across all swimming strokes, as well as its component parts (i.e. arm and leg-only component), across different levels of swimmers specialising in different events. This could be used to formulate normative data, to help coaches prescribe individualised training. Furthermore, the approach of estimating thresholds demarcating moderate and/or extreme domains from CS could be examined in all strokes in order to provide coaches with estimated values they could use if they do not have access to IST. The validity of this approach could be also assessed against thresholds extracted from IST and across different levels of swimmers.

Given that the importance of CS and D' will likely vary depending on the event the swimmer specialises in (as distance increases CS becomes stronger predictor than D' and vice versa), future studies could investigate optimal training designs of depletions schemes for sprint, middle and long-distance swimmers, and demonstrate their effects on CS and D', as well as their effect in comparison to a control group completing traditional HIIT approaches utilised by coaches (e.g., all-out, best average). These types of future studies could also investigate the long-term effects of training programmes prescribed based on CS and CSR concepts in order to see if the effects we observed in chapter 5 would change as a result of time. In addition, given the lack of a control group in chapter 5, future studies could also examine physiological responses ($\dot{V}O_2$, HR, blood lactate) in HIIT prescribed based on CS, D', CSR (e.g., various depletion schemes, HIIT efficiency sets) and perhaps compare these responses to those elicited by HIIT typically utilised by coaches. Similarly, future studies could examine the effect of individualised warm-ups based on CS and D' (severe domain) versus typically prescribed warm-ups (self-selected, moderate, heavy) on subsequent swimming performance. In addition, as previously explored in cycling (Townsend et al., 2017), future studies could explore the impact of hypoxia (different levels of altitude) on CS and D' parameters in order to illustrate what changes can be expected in these parameters when swimmers go to different altitudes, thus allowing coaches to make more informed decisions about training prescriptions in this environment.

To help elucidate the ongoing 'Quantity versus Quality' debate in swimming, future studies could simultaneously compare the impact of these training programmes (e.g., the concepts discussed in this PhD and high-volume training programmes typically utilised by coaches) to examine their effect on training adaptations (e.g. physiological, technical, performance, HRV, subjective wellness measures). In addition to this, the effectiveness of a HRV-guided approach compared to a predetermined training approach could be also explored in swimming, given the volume of training the swimmers typically complete. Collection of this data could be further used to examine whether HRV and/or performance responses could be modelled and/or predicted in the future using the I-R model, or more advanced machine learning methods. If the I-R method is to be utilised to model HRV, future research should first explore various approaches of data collection to see if the HRV can be modelled to a better extent than in the present thesis. Indeed, whilst the aim of chapter 6 was to utilise feasible

approaches, athletes reporting sRPE for the previous day's activity instead of 30 min post each training session could have compromised validity of the model's input, despite previous research suggesting that sRPE is temporally robust up to 24 h post-exercise (Christen et al., 2016). Therefore, collecting sRPE post each session, or perhaps utilising alternative training load methods that are still practically feasible (e.g., volume below and above CS), could better capture the training 'dose'. Furthermore, measuring HRV via smartphone PPG method is still a relatively novel approach to HRV monitoring and whilst the HRV4Training app utilised in this PhD has been successfully validated against ECG and the Polar H7 chest strap, additional *independent* validation studies are warranted. This is primarily due to the PPG method requiring limited finger movement during collection, as well as the sensitivity of PPG to pressure applied on the camera. Therefore, future studies could perhaps simultaneously utilise PPG and HR straps in a longitudinal manner in order to see the agreement between methods.

Given that some of the proposed work for future studies will be undoubtedly difficult to conduct, the community of sport scientists and practitioners will likely answer some of these questions in their own practice, and others by exchanging experiences with fellow practitioners. In order to share these with wider audience, these can be subsequently promoted as evidence-based practice by publishing educational commentaries that combine the best available knowledge, research methodologies, and practitioners' expertise (Coutts, 2017). Indeed, this approach has been recently emphasised as one of the tools that will help us to bridge the gap between science and practice, and as Martin Buchheit (2017) once suggested, will help sport sciences back from orbit to Earth, where the questions such as "Will this make me faster or win more medals" need to be answered to those who sport sciences are meant to help: coaches and athletes.

7.7 Conclusion

The aim of this PhD was to produce a body of work that could contribute to bridging the gap between science and practice in testing, training prescription and monitoring and therefore assist swimming practitioners (mainly coaches) with utilising methods that are both valid and feasible to conduct on a regular basis. In order to achieve this aim, four research studies were formulated and addressed in this PhD. Firstly, the 3MT

was demonstrated to be a valid, reliable and feasible tool for measuring CS and D' parameters in highly-trained swimmers. Subsequently, further application of 3MT for estimating the remaining exercise intensity domains was explored and was shown to outperform the popular 'beats below HR_{MAX} ' method. In the third study, the ideas of CS and CSR concepts were applied to a reduced-volume training programme of highly-trained swimmers, which was shown to elicit meaningful improvements in several parameters of swimming performance despite a $\geq 25\%$ reduction in swimming volume. Finally, additional data collected via a novel smartphone application (HRV, sRPE and subjective wellness scores) enabled modelling of HRV responses to swimming training and non-training related stressors via the I-R model during this period. Large relationships observed between seasonal changes in key HRV parameters and CS provided further evidence for incorporating a HRV-guided training prescription approach as a tool to optimise training programmes and performance outcomes of competitive swimmers.

All in all, it is hoped that this body of work has contributed to closing the gap between science and practice in the investigated areas. The authors also hope that this work will stimulate similarly minded future research to continue helping swimming coaches to design and deliver training programmes, allowing swimmers to maximise their performance potential.

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